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THESIS

ASSESSING MOTION INDUCED INTERRUPTIONS USING A MOTION PLATFORM

by

Gregory E. Gehl

September 2013

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Human performance contributes to total system performance. As human performance decreases, total system performance decreases while lifecycle costs increase. In a fiscally constrained environment, Human Systems Integration (HSI) seeks to assure human performance to reduce operating costs. This thesis seeks to develop a model for ship design in relation to Motion Induced Interruptions (MII). The model is based on the premise that MIIs affect specific domains of HSI in an adverse way. Future ship design considerations that mitigate MII occurrences can save the Navy money spent on human injury and system degradation. The thesis begins with an historical overview of MII theory and development and its interactions with domains of HSI. A MII prediction model was developed using data acquired from an experiment using a motion-based platform that emulates ship motion. Quantitative data were analyzed from 21 subjects who underwent 32 trials. Multiple regression analysis consisted of two independent variables as period and lateral acceleration and the response variable as a MII incident. Logistic regression considered two more independent variables that addressed individual differences. Data analysis revealed that acceleration, period, and human balance were statistically significant. The proposed multiple regression model accounted for 77% of the variance of MII forecasting. This thesis lays the foundation for future quantitative analysis of interactions between MIIs and accelerations or periods in different axes. Additionally, it provides an initial model that predicts conditions of high MII incident environments that can ultimately lead to a viable design tool for HSI practitioners and ship designers.

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ASSESSING MOTION INDUCED INTERRUPTIONS USING A MOTION PLATFORM

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Human performance contributes to total system performance. As human performance decreases, total system performance decreases while lifecycle costs increase. In a fiscally constrained environment, Human Systems Integration (HSI) seeks to assure human performance to reduce operating costs. This thesis seeks to develop a model for ship design in relation to Motion Induced Interruptions (MII). The model is based on the premise that MIIs affect specific domains of HSI in an adverse way. Future ship design considerations that mitigate MII occurrences can save the Navy money spent on human injury and system degradation. The thesis begins with an historical overview of MII theory and development and its interactions with domains of HSI. A MII prediction model was developed using data acquired from an experiment using a motion-based platform that emulates ship motion. Quantitative data were analyzed from 21 subjects who underwent 32 trials. Multiple regression analysis consisted of two independent variables as period and lateral acceleration and the response variable as a MII incident. Logistic regression considered two more independent variables that addressed individual differences. Data analysis revealed that acceleration, period, and human balance were statistically significant. The proposed multiple regression model accounted for 77% of the variance of MII forecasting. This thesis lays the foundation for future quantitative analysis of interactions between MIIs and accelerations or periods in different axes. Additionally, it provides an initial model that predicts conditions of high MII incident environments that can ultimately lead to a viable design tool for HSI practitioners and ship designers.

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LIST OF ACRONYMS AND ABBREVIATIONS

CM	Corrective Maintenance
COG	Center of Gravity
COM	Center of Mass
DAU	Defense Acquisition University
DoD	Department of Defense
DoF	Degrees of Freedom
DOTLPF	Doctrine, Organization, Training, Leadership, Personnel, Facilities
DV	Dependent Variable
ESOH	Environmental Safety Occupational Health
FOG	Foot Off Ground MIIs
HFE	Human Factors Engineering
HIL	Human in the Loop
HOG	Heel Off Ground MIIs
HSI	Human Systems Integration
LCPL	Landing Craft Personnel Large
LFE	Lateral Force Estimator
MSAQ	Motion Sickness Assessment Questionnaire
MII	Motion -induced interruption
NBDL	Naval Biodynamics Lab
NPS	Naval Postgraduate School
NSWC PC	NSWC Panama City
PI	principal investigator
PM	preventative maintenance
RHIB	Rigid Hulled Inflatable Boat
RMS	Root Mean Squared
SMS	Ship Motion Simulator

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EXECUTIVE SUMMARY

This thesis provides a qualitative and quantitative evaluation of motion-induced interruptions (MII) and its relationship to Human Systems Integration (HSI). The qualitative evaluation consisted of an in-depth discussion of MII theory and development. The qualitative analysis also consisted of a description of how MIIs interact with domains of HSI with respect to ship design. The quantitative evaluation consisted of the relationship between environmental and individual human factors with MIIs. The analysis consisted of both multiple regression and logistic regression. Multiple regression was necessary to determine which combinations of lateral acceleration and period most likely accounted for variability. These combinations were used to fit a model capable of predicting MII incidence. Logistic regression was used to determine whether individual differences, such as balance ability or a person's stance in relation to his center of gravity (COG), affected MII occurrence. This thesis concluded that period of acceleration was significant when predicting the probability of MII occurrences. Human balance ability was also a significant factor. The findings of these analyses lay the groundwork for future quantitative analysis that considers the period variable when attempting to predict MIIs. Recommendations for future research include further qualitative and quantitative analysis of accelerations and periods that cover greater ranges over varying axes, continued refinement of equations that predict MIIs, future inputs of MII theory in ship design, and analysis of the trade spaces between HSI domains in relation to MIIs. A limitation of this study was the limited range of the motion base system that constrained the ability to use higher values of acceleration, which would lead to greater incidence of MII. Additionally, the study considered only performance degradation related to physically falling and tipping and did not account for cognitive human tasks.

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I. INTRODUCTION

A. PROBLEM STATEMENT

Motion Induced Interruptions (MIIs) are changes of stance that lead to a stop in work (Wedge & Langlois, 2003). Baitis, Applebee, & McNamara (1984) first stated a simple definition tailored to the Navy as the lack or loss of balance produced by large ship motions and wind loads. MIIs are the human responses to dynamic motion environments onboard marine vessels where postural stability is significantly degraded. Effects of MIIs consist of slips, trips, and falls plus task interruptions that may have adverse effects on human performance, such as degraded performance, discomfort, or injury. These outcomes in turn can lead to system performance degradation. Previous research has developed quantifiable MII criteria to predict the probability of MIIs per type of task under certain dynamic environments. Graham (1990) has proposed predictor equations that estimate the probability of MIIs based on the "tipping factor."

Graham considered tipping to be related to a stumble by a human onboard the deck of a surface vessel. Ship motion can be characterized by three axes of angular motion—yaw, pitch, and roll, and three linear axes—heave, surge, and sway. Graham (1990) developed a series of equations to predict the incidence MIIs of a human stick figure (or rigid body model) as a function of a person's COG and width of stance. Unfortunately, recent research at the Naval Postgraduate School (NPS) has found that the tipping factor overestimates the probability of a MII (McCauley, Pierce, & Matsagas, 2007). The reason for the overestimation may be the fact that a human 'is not a static object but rather a dynamic complicated response system that is constantly correcting itself to maintain an optimal COG to maintain balance.

The goal of this study is to test the hypothesis that sway acceleration, period, tipping coefficient, and Sharpened Romberg scores would influence MIIs. Another goal is to develop MII predictors based on empirical data to either improve the accuracy of Graham's Tipping Equation or replace it with a better equation, as well as provide insights that may improve seakeeping criteria. The outcome of this study will enable ship

captains to predict more accurately when MII's might pose risk to crew performance in the course of ship operations. Naval architects and ship designers also may be able to improve the design of new platforms with more accurate information about when MIIs are relatively likely to occur.

B. OBJECTIVES

The research intends to define and explain the relationship between environmental factors and individual differences with MMIs.

- Assess how sway axis period and acceleration impact the occurrence of MIIs
    - Wide ranges of linear accelerations and frequencies that can have an effect on MIIs
- Assess how individual specific traits impact the occurrence of MIIs
    - Individuals have different stance widths in relationship to their center of mass. Individuals also have different balance abilities
- Develop and assess a model capable of explaining the relationships between ship motion and individual traits with MII occurrences
- Ascertain whether the thesis results compare with Graham's Tipping Equation.
    - The literature review discusses research that finds over-prediction with Graham's equations

C. RESEARCH QUESTIONS

- What types of acceleration and period contribute to MIIs and how important is acceleration and frequency?
- Is there a relationship between an individual's tipping coefficient and MIIs?
- Is there a relationship between an individual's balance ability and MIIs?
- Can we use laboratory data to derive a model that predicts the relative likelihood of MIIs?
- Does the model support using Graham's Tipping Equation?

D. HUMAN SYSTEMS INTEGRATION (HSI)

The NPS (2010) definition of HSI states:

> HSI acknowledges that the human is a critical component in any complex system. It is an interdisciplinary approach that makes explicit the underlying tradeoffs across the HSI domains, facilitation optimization of total system performance in material and non-material Doctrine, Organization, Training, Leadership, Personnel, Facilities (DOTLPF) solutions to address the capability needs of organizations.

Military systems depend on humans as an integral part of an effective design. If weaknesses in domains can be identified in a particular system, implementing the HSI process will optimize system performance and reduce life cycle costs over the long run. The HSI domains (Booher, 2003) include the following:

- Manpower
- Personnel
- Training
- Human Factors Engineering
- Environmental Safety and Occupational Health
- Habitability
- Survivability

Tradeoffs are made among domains in system acquisition using measures of performance and effectiveness to regulate performance. Manpower, human factors engineering, and environmental safety and occupational health will be addressed in this thesis by considering performance degradation and human injury or system loss. The incidence of MIIs on ships has considerable potential for reducing mission effectiveness and efficiency. Accordingly, it is important to consider the tradeoff implications among these domains when thinking about ship design and MIIs.

1. Human Factors Engineering

The Defense Acquisition University (DAU) defines human factors engineering as "The discipline of applying what is known about human capabilities and limitations to the design of products, processes, systems, and work environment. It can be applied to the design of all systems having a human interface, including hardware and software"

(Defense Acquisition Guidebook, 2010, p. 6.3.4). The proposed research will provide information to ship designers that will enable improved design for human stability and performance. Potential hazards from tasks conducted by personnel onboard naval vessels pose a need for better ship design to account for performance degradation from environmental stressors. Tipping of personnel caused by motion from various levels of sea state can cause injury and human performance degradation, and can potentially lead to mission failure. Human Factors Engineering can contribute ways to design deck surfaces, ship hulls, and body support structures to help mitigate the negative effects of MII's on human performance. Better design in regards to how the sailor interfaces with the ship also can lead to improved boat and helicopter operations.

2. Environmental Safety and Occupational Health

DAU defines environmental as "the natural and manmade conditions in and around the system and the operational context within which the system will be operated and supported. This environment affects the human's ability to function as a part of the system" (Defense Acquisition Guidebook, 2010, p.6.3.5). DAU defines safety as "factors consisting of those system design characteristics that serve to minimize the potential for mishaps causing death or injury to operators, maintainers, and supporters or threaten the survival and/or operation of the system" (Defense Acquisition Guidebook, 2010). DAU defines occupational health as "factors of system design features that serve to minimize the risk of injury, acute or chronic illness, or disability; and/or reduce job performance of personnel who operate, maintain, or support the system."

The Navy is interested in ways to mitigate risk when it comes to safety of personnel and mission success. Navy ships operate in various weather conditions that can lead to undesirable motion. If a MII occurs while a sailor is performing a high-risk task like boat and flight operations or handling heavy equipment under an elevated sea state, the sailor could experience physical harm, as well as put missions in jeopardy. Unfortunately, Navy operations sometimes must be accomplished under unsafe conditions due to mission priority. This problem guarantees that mishaps related to MII's are going to happen. This thesis is intended to provide insight into the probability of

someone experiencing a MII under different motion conditions. This insight can give decision makers a better picture of the risk of an injury under various weather environments.

3. Manpower

DAU defines manpower as “job tasks, operation/maintenance rates, associated workload, and operational conditions that are used to determine the number and mix of military and DoD civilian manpower and contract support necessary to operate, maintain, support, and provide training for a system” (Defense Acquisition Guidebook, 2010, 6.3.1). MIIs lead to poor performance due to injuries; therefore, more manpower may be needed to replace the injured sailor who is injured. More manpower also could be needed to offset the reduction in time to complete tasks and the reduction in effectiveness due to performance degradation. Insight from this thesis is intended to support better manpower assessments based on the risk of potential sailor casualties and the crew size needed to complete tasks under motion conditions that result in MIIs.

E. THESIS ORGANIZATION

This thesis is comprised of six chapters. Chapter I provides the problem statement and introduces the specific HSI domains relevant to this case. Chapter II consists of the literature review of MIIs and its relationship with selected HSI domains. Additionally, the review discusses the relationships between the specific factors outlined in the objectives section and MIIs. Chapter III discusses the methodology of the experimental design using a motion base to assess MIIs. Chapter IV includes qualitative and quantitative analyses and model building. Chapter V interprets the results and discusses their implications. Chapter VI provides conclusions and makes recommendations for further research.

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II. LITERATURE REVIEW

A. OVERVIEW

The literature review is divided into four parts. The first three parts consist of an overview of MIIs, Graham’s Tipping Equation, and the Sharpened Romberg Test. The last part describes an overview of naval systems and evolutions affected by MIIs, and summarizes the relationships they have to HSI domains pertaining to this thesis.

B. INTRODUCTION

Investigators have analyzed the physics and the dynamics of human postural equilibrium aboard ships since the 1980s. This research led to more explicit criteria for ship design (Graham, 1990). The investigators concluded that tipping, sliding, and lift-off were the three factors defining MII’s. The tipping aspect is a stumble that occurs when a human stands on a moving marine platform. Graham and others have used this tipping component to derive equations that attempt to predict MIIs. The problem with the human “tipping” equations is that they treat humans as a rigid structure. These tipping equations over-predict MIIs because they assume that once enough force is exerted to disrupt ’peoples’ COG, they will lose their balance, but does not’ account for other factors, such as the natural human tendency to balance and correct actively for the motion to maintain postural equilibrium.

Graham (1990) developed a model for MII prediction based on the function of stance geometry and the height of a human’s center of gravity. His equations include tipping to port, starboard, aft, and forward, which is influenced by lateral and longitudinal motions. The tipping coefficient is based on a person’s center of mass (COM) and stance width. Considerable work has been done to validate the equations empirically and the results determine that the tipping coefficients substantially over-predict MII occurrence (Crossland & Rich, 1996). Other researchers suggest including various levels of acceleration and motions in different axis like pitch and roll to emulate large seas states (McCauley, Matsagas, & Miller, 2005). Graham’s Tipping Equation does not consider the amount of time (e.g., the period) that a lateral, linear (sway) acceleration is applied.

This thesis aims to provide insight into significance of period when applied over various accelerations to determine human limits to predict MIIs. This approach may create more accurate MII forecasting, enabling naval architects to design more effective hulls and workstations that reduce mishaps and performance degradation.

The scope of this thesis is limited to the aspect of MIIs that pertain only to whole-body vibration and motion. A person's stance width in relation to height along with a person's balance ability are potential individual factors that influence MIIs. This thesis aims to provide insight into these possible predictor variables of MIIs and the relationship to HSI. Naval architects and future ship designers can reduce adverse effects of MIIs by incorporating this research area with the HSI domain trade spaces. The next section of the literature review discusses the historical development of MII theory.

C. MOTION-INDUCED INTERRUPTIONS

Much research has been conducted over the past two decades on ship motion and its effect on human performance (Ross, 2009). One element studied during that time was the degrading effects MIIs have on sailors, which include injury, operational mishap, and whole-body vibrations. For the scope of this thesis, MIIs and the relationship between MIIs and task performance is the central focus of the literature review. To understand the relationship between MIIs and future ship design, it is necessary to understand the theory and causal factors of MIIs.

Before discussing the effects of MIIs, it is first necessary to understand the definition of "Motion Induced Interruption." Baitis, Applebee and McNamara (1984) first stated a simple definition referenced in the introduction as the lack or loss of balance produced by large ship motions and wind loads. Baitis, Applebee and McNamara used the term MII as a classification that considers several human biodynamic problems including motion sickness, whole-body vibration, and discomfort. Traditional methods of developing ship design criteria to minimize biodynamic problems have been ineffective due to the wide range of different types of seagoing vessels. MII research is attempting to produce reliable and accurate MII occurrences to promote crew safety and human

performance. Accurate and reliable MII prediction will support improved design guidelines for new naval vessels and possibly advance standard seakeeping criteria.

The failure of traditional methods to predict human performance degradation spawned the idea for developing MII criteria. An example of a traditional method is root mean squared (RMS) value of roll. Credible references exist on common seakeeping procedures in the ship design process. The recommended constraint for personnel operations is four degrees of roll, which is predicted to result in about one MII per minute (NATO STANAG 4154, 1998). Table 1 shows the maximum values of roll angles and accelerations for operability criteria. It must be noticed that time and periods are also absent as they are in other MII research.

Table 1. Operability Criteria (From Stevens & Parsons, 2002)

	NATO STANAG 4154 (U.S. Navy)	U.S. Coast Guard Cutter Certification Plan
Motion Sickness Incident (MSI)	20% of crew in 4 hours	5% in a 30 minute exposure
Motion Induced Interruption (MII)	1 tip per minute	2.1 tips per minute
Roll amplitude	4.0° RMS	8.0° SSA
Pitch amplitude	1.5° RMS	3.0° SSA
Vertical Acceleration	0.2 g RMS	0.4 g SSA
Lateral Acceleration	0.1 g RMS	0.2 g SSA
Operability Criteria (RMS = Root Mean Square; SSA = Significant Single Amplitude; SSA = 2 x [RMS])		

These values are hardly enough to curtail operations (Stevens & Parsons, 2002). Baitis et al. (1994, p.67) states that it is not the inclination of the angle of roll but the level of acceleration associated with MIIs. McLeod et. al. (1980) and Baitis et al. (1984) began examining the physics associated with the human standing response to deck dynamics from simulations and observations of the crew during helicopter recoveries aboard ships. This analysis led to three MII classes called tipping, sliding, and lift off. This thesis deals with the tipping aspect of MIIs. Tipping involves humans standing upright on a deck with their feet spaced normally and being exposed to a ship motion that causes one or both feet to move, that could lead to a stumble or fall. This “tipping” creates a moment of time in which the sailor’s attention and effort is potentially shifted from the job task to the struggle to maintain balance.

McLeod and Poulton (1980) were the first to study the effects of motion on human performance by using a simulator. They studied human tasks related to motor skills. The simulator emulated the motion of a British frigate. The result of the study found that the task of tracing using a pencil led to severe performance degradation. Baitis et al. (1984) studied the execution of human tasks involving helicopter recoveries. They used a simulation of a FFG-8 Oliver Hazard Perry class frigate. The tasks involved common ship-related events, such as recovering a helicopter by hooking up a line, preparing the helicopter for traversing across the deck, and stowing the helicopter in the hanger. These tasks were used because they included the elements of walking, standing in one place, and motor ability. MIIs were found resulting from deck acceleration influenced by ship movement and were recorded as sliding, tipping and falling. This thesis will deal with the deck accelerations related to lateral motion defined in the sway axis, which is the right left linear motion on a ship. The ship motion, translated to the position of the human, is described in three translational (linear) degrees of freedom (surge D_1, sway D_2, and heave D_3) and three rotational degrees of freedom (roll η_1, pitch η_2, and yaw η_3) as shown in Figure 1.

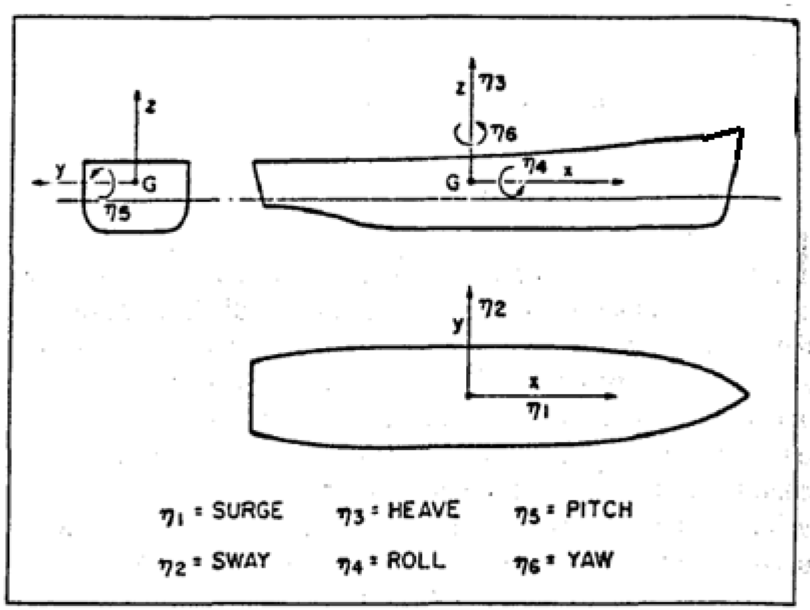

Figure 1. Axis System (From Graham, 1990)

Other elements of ship motion, such as heave, may have an effect in MII prediction. However, to keep the scope of this thesis manageable, only sway (lateral linear motion in the y axis, was examined alone and in combination with pitch and roll. The data on pitch and roll will be analyzed in a separate report.

D. GRAHAM'S TIPPING EQUATION

In the 1990's, Graham formulated a model that attempts to predict MIIs based on deck lateral and longitudinal accelerations, roll, and tipping coefficient related to the physical human body. Graham et al. (1992) developed quantifiable seakeeping criteria by developing his Tipping Equation, which attempted to predict MII occurrence. This equation takes into account the loss of balance events associated with MIIs. A lateral force estimator (LFE) was developed to predict MIIs given a person's geometry and the particular environmental force experienced. Graham developed equations for the different ship motions and experiences, such as pitch and roll but for this thesis, the focus will be on the lateral motion or sway. Previous research has shown that a majority of MIIs occur in the lateral directions off the beam of ships, as illustrated in Figure 3. Accordingly, Crossland (1993) suggested dealing only with lateral accelerations.

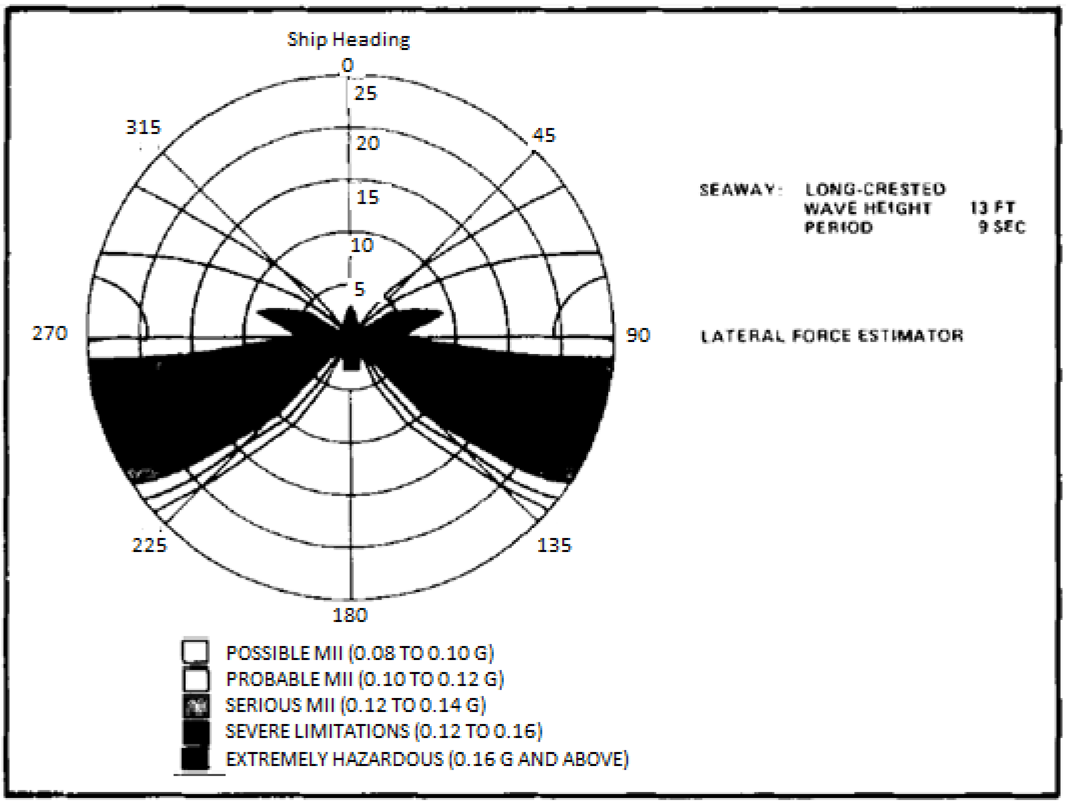

Figure 2. Ship Motion Envelope and Areas and of Risk Due to MII (From Baitis et al., 1984)

Figure 2 is a chart that shows ranges of lateral acceleration (G force) that translate into MII frequency predictions ranging from possible to extremely hazardous. The concentric circles represent ship's speed and the polar labels represent ship heading. One purpose of this figure is to illustrate the high percentage of MIIs that occur with sway axis acceleration. The range of 0.08 to 0.16 G provided initial guidance for the design of the experiment in the present research. The experiment will reexamine the relationship between MIIs and the levels of lateral acceleration.

One of Graham's major assumptions in formulating his equations was that humans are a rigid structure, such as a stick figure, prone to tip-over from environmental forces that equal or exceed their center of gravity. He related center of gravity to a person's stance width. Figure 3 depicts a person and shows the two variables used in calculating Graham's tipping coefficient.

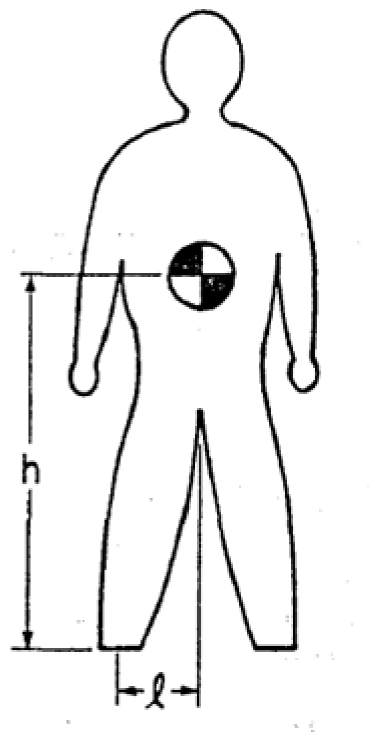

Figure 3. Model on Deck for a Person Facing Forward or Aft (From Baitis et al., 1995)

These criteria were used to develop two lateral tipping equations to predict MII shown in Equations 1 and 2.

$$-g\eta_4 - \ddot{D}_2 - \frac{l}{h}\ddot{D}_3 > \frac{l}{h}g \text{ (tip to port)}$$

Equation 1. Graham's Tipping Equation to Port (From Graham, 1990, p. 67)

$$g\eta_4 + \ddot{D}_2 - \frac{l}{h}\ddot{D}_3 > \frac{l}{h}g \text{ (tip to starboard)}$$

Equation 2. Graham's Tipping Equation to Starboard (From Graham, 1990, p. 67)

The right side of each equation reflects a person's tipping coefficient and the left side of the equations contain Graham's LFE: g is the acceleration of gravity, η_4 is the ship roll angle (positive clockwise, looking forward), $\ddot{D}_2$ is the lateral acceleration (positive left, looking forward), $\ddot{D}_3$ is the vertical acceleration (positive up), h is the distance from the human CG to the deck, and l is the human half-stance distance.

A study conducted by Baitis (1995) attempted to validate Graham's Tipping Equations. Baitis used the Naval Biodynamics Lab (NBDL) Ship Motion Simulator (SMS), which produced pitch, roll, and heave motions but not lateral (sway) accelerations. Subjects were fitted with seven-pound back packs measuring the center of gravity of motion and were asked to stand, walk, and hold objects. Subjects underwent various sea conditions and MIIs were recorded based on foot movement made to stabilize balance. The shifting of feet was observed, which increased their tipping coefficient.

This experiment concluded that Graham's Tipping Equations tend to over-predict MII occurrence. However, the prediction was much better than the traditional use of only ship roll information. One idea for Graham's over-prediction is the fact that humans are more than just a rigid structure that can be tipped over once enough lateral force is present. Humans are complex and flexible beings that can compensate for deck motions by training, correcting, stabilizing, and anticipating acceleration from previous experiences. The NPS research team noticed the absence of time or period of acceleration as a factor considered in earlier research. How long a person endures a particular acceleration may have an effect on whether an MII will occur. For this reason, period is tested as a potential MII predictor in this thesis. If period turns out to be a significant predictor, this finding could improve the accuracy of Graham's Tipping Equation.

E. SHARPENED ROMBERG TEST

'Physicians use the Sharpened Romberg Test to evaluate a person's balance abilities. It is also commonly used for impaired driving determinations (Bridge, 1972). The assessment gives insight into a person's proprioception, which is the sense of the relative position of neighboring parts of the body and strength of effort being employed in movement. Conditions that affect a person's proprioception can cause imbalances that lead to unwarranted tripping and falling. For the scope of this thesis, proprioception is associated with balance. If MII's occur more frequently with individuals who perform poorly on the Sharpened Romberg Test, this variable could be a potential predictor of MIIs.

Moritz Heinrich von Romberg first described the integrity of the dorsal columns of the spinal cord in the early 19th century, which led to his development of the Romberg test for assessing the pathology of the proprioceptive pathway (Khasnis, 2003). The Sharpened Romberg Test is a modification of the original test to account for vestibular and cerebellar impairment (Lanska & Goetz, 2000). The test is normally used as a simple way to assess sensory ataxia, which causes the postural imbalance. Many factors can inhibit a person's proprioception or balance abilities. Hereditary factors range from autosomal dominant sensory ataxic neuropathy to Biemond Syndrome (Khasnis, 2003). The major purpose of outlining some of the causal factors of individual imbalance is to show that many factors can contribute to a person's balancing abilities. The scope of this thesis will only deal with the question of whether poor balance as measured by the Sharpened Romberg Test serve as a predictor variable for MIIs.

The procedure is a simple one that instructs the subject to assume a specific stance and hold it for a period of time. The Sharpened Romberg Test, as originally described by Fregly and Grabiel (1966), involved the subject "standing on the floor with eyes closed and with arms folded against chest, feet aligned in strict tandem heel-to-toe position, and body very nearly, if not completely erect for a period of 60 seconds" (Fregly & Grabiel, 1966, p. 3). A stopwatch is used to record how long individuals can maintain their balance by the visual indication of significant swaying or movement of the feet to restore their balance. Learning effects occur with this test and at least two trials should be performed to obtain an accurate reading (Lee, 1998). If performing an experiment, fatigue can result and is why it is recommended to administer the test prior to the experiment. Other obvious factors that can influence Sharpened Romberg scores include alcohol and fatigue.

Results from the Sharpened Romberg Test can give insight to an individual's inherent balancing abilities. Lanska and Goetz (2000) reported the use of quantitative, computer-calculated Romberg's test and concluded it is a reasonable way of measuring postural stability. They also suggest that Romberg's test scores have contributed

significantly to the development of mechanical modalities like computerized dynamic platform posturography for measuring postural stability. If one person demonstrates poor balance abilities, that may be a predictor of MII's.

F. NAVAL SYSTEMS AFFECTED

Working in a moving environment can create many hazards that can result in human injury and loss of work. Wertheim (1998) classified effects of human performance into general and specific effects. General effects are related to performance and job tasks of a biomechanical nature. Examples would be turning a wrench or climbing a ladder. Degrading effects can be induced by motion sickness or the ability to maintain 'balance. Specific effects are related to performance and job tasks of the cognitive nature. Examples would be an Operations Specialist on a ship who keeps track of radar contacts or a pilot balancing the workload of combat and flying in an F-18 fighter jet. Wertheim conducted a review of research that investigates how working in a moving environment can affect performance and the findings relate to tasks associated on United States (U.S.) Navy ships. Such tasks are small boat and helicopter operations, medical response, and engineering maintenance.

Wertheim (1998) also reviewed the investigation of balance problems related to postural control using motion platforms. Accelerations from ship motion create balance problems. Studies from Graham (1990) and Baitis (1994) dealt with humans standing in the upright position and recording losses or near losses of balance. Biomechanical models were developed to predict the frequency of MIIs in given sea states to develop sea-keeping criteria to determine whether conditions at sea were safe or dangerous to complete a designated task. Motor tasks involving the movement of arms, hands, and fingers was first studied by McLeod et al. (1980) in a motion simulator. Results showed degradation of fine motor control. Crossland and Lloyd (1996) conducted a simulator motion study involving paper and pencil tests, which also found motor control degradation. This evidence suggests that movement interference creates MIIs caused by biomechanical factors and leads to motor control degradation. Motor control is an

important factor when handling a small boat, connecting chains to an approaching helicopter on a ship, applying medical attention, and performing maintenance tasks.

Specific tasks also were analyzed that relate to cognitive and perceptual factors. Wertheim (1998) found from a simulator motion study that perceptual performance degradation occurred when subjects had to identify a particular target letter presented within briefly visible arrays of letters on a computer monitor. Visual blur from ship motion, caused by the reflexive nystagmoid eye movements, was attributed to the performance degradation. Other studies reviewed by Wertheim concluded that although specific cognitive tasks were not degraded by ship motion, tasks that dealt with biomechanical factors could expect to see varying levels of performance degradation (Wertheim, 1998).

This research analysis shows how performance degradation in human motor and perceptual capability can occur from ship motion. Therefore, it is important to discuss related activities on ships where mishaps can occur from these potential motor and perceptual performance degradations. Small boat operations are common on Navy ships that involve launching a RHIB (Rigid Hulled Inflatable Boat) or an LCPL (Landing Craft Personnel Large). This complex task involves a crew who helps launch and recover the boat from the ship, as well as the crew inside the boat who operate it after its launch. The task involves a set of rapid events where the ship maneuvers itself against the wind to create a lee that provides the calmest sea conditions available at the time of launching the boat. Even in sea states of three, it can be difficult to maintain the proper direction of the ship. Once a proper lee is established, linesmen alongside the boat heave out the lines attached to the boat, which controls the slow descent of the boat into the water. Then, the crew in the boat must release lines under heavy tension and other heavy hooks attached to the ship. A reverse sequence is followed when retrieving the boat back onboard a ship. Throughout this process, if the boat encounters harsh waves, it can create severe MIIs that can result in lost limbs, concussion, and man overboards. The coxswain, the operator of the boat, must be precise in keeping the boat perfectly aligned next to the ship. A MII experienced by the coxswain can cause him to accidentally maneuver the boat and trap bodies or limbs between the small boat and the side of the ship.

The launch and recovery and shipboard refueling of helicopters onboard ships is another Navy operation susceptible to biomechanical influence and mishap-prone environments. Most tasks involved in launch and recovery depend on the stability of sailors and their ability to perform in a moving environment, often while holding equipment. The initial hook-up of the helicopter messenger line with the RAST system was identified as a hazardous condition susceptible to MIIs (Baitis et al., 1984). Other equally hazardous activities included the traverse of the helicopter to and from the hanger. Aircraft handling and chock crewman normally wear blue jerseys aboard ships with flight decks that launch helicopters (Flight Deck Awareness, 2008). These sailors are responsible for the handling and securing of aircraft with wheel chocks and chains. as well as the handling equipment that includes tractors and aircraft starting units. Many of the moving parts require the safe and effective handling of this equipment when releasing or stowing a helicopter. Unexpected movements caused by sailors losing ’their balance can lead to the improper securing of a helicopter, as well as bodily harm from the tension and weight of chains. One incident occurred aboard an aircraft carrier in 2006 that involved a sailor who lost his balance and fell off the flight deck into the water. Numerous injuries occurred while sailors lost footing when transiting down latters while carrying bulky objects (Safety Training Gouge, 2012, p. 3). Another occurred when a marine aviation handler lost part of his finger from contact with a tail hook when he stumbled underneath an F/A 18 while doing last minute checks (Flight Deck Awareness, 2008). Thus, it can appreciated how these tasks would become extremely hazardous under heavy seas and wind conditions contributing to MIIs.

This research also is relevant to common procedures related to medical response or supply handling. In the event of a massive casualty situation in harsh conditions, the effective application of medical care can be inhibited due to motor control degradation. Response times may be reduced and equipment can break from tripping and falling. Normal supply handling of heavy boxes poses a risk because it changes the person’s tipping coefficient. A sailor’s balance might be more vulnerable due to the altered tipping coefficient. In sum, many activities performed by sailors on ships are vulnerable to potentially costly and dangerous MIIs.

G. OVERVIEW OF RELEVANT HUMAN SYSTEMS INTEGRATION DOMAINS

Changes in ship design impact the trade space of HSI domains. This section of the literature review discusses the three most relevant domains and describes the relationship they have to MIIs. In addition, design changes in one HSI domain affecting other domains, as well as cost and performance, is also discussed.

1. Manpower

As the Navy reduces manpower onboard ships, the interaction between sailor and machinery becomes more important. When manpower decreases, the workload of either the operator or the machine must increase. A higher workload for the operator generally will increase the risk of mishaps over time. Unless the machines work flawlessly, errors and emergency situations will occur from time to time. Risk of error and emergency exist even in normal situations. Low manpower increases those risks due to fatigue and higher workloads. Risk increases further in high sea states due to MIIs.

High motion environments increase the probability of MII occurrence. MIIs can cause performance degradation of fine motor skills. Physical limitations on humans include standing, walking, operational and maintenance task and mechanical operations (Dobie, 2000). If systems are not tailored properly to meet potential challenges under high ship motion environments, major problems can arise. In 2002, the Center for Naval Analysis conducted a study to assess the Navy's manpower requirements (Moore, Hattiangadi, Sicilia, & Gasch, 2002). One of the questions was to find the major drivers of manpower requirements. Several findings included watch standing, corrective and preventative maintenance, and workload as major factors. All these factors are increased under extreme ship motion environments.

The Office of Naval Research conducted Human in the Loop (HIL) data collection using self-reporting and observation. The results determined that MIIs led to decreased assessments of percent of task completed and increased time on task (Naval Air Warfare Center Training Systems Division, 2011). Link interruptions with the operational environment also occurred. Ship manning should consider the potential for

mistakes and operator error under heavy seas. As MIIs increase, more manpower will be needed to correct mistakes that have been made, such as operating switchboards or maintain course during an underway replenishment. If sufficient manning is not in place, mishaps will create costly situations for repair and redesign.

2. Environmental Safety and Occupational Health

Operating on a moving platform increases the potential for human performance degradation and injury. MIIs are one of the causes of performance degradation in this situation and heavy seas create environments for increased MII frequency. MIIs create a loss of balance that can be devastating under certain shipboard activities as mentioned previously in the literature review.

The Navy Safety and Environmental Training Center reported sailors falling from ladders as a very common shipboard mishap. Ladders are inclined at 68 degrees, and as sailors traverse them within the ship, unanticipated waves can cause trips and slips that can result in the sailor falling and potentially breaking bones or even worse. The conditions are magnified if the ladders are wet from poor weather.

Small boat operations, helicopter operations, and over the side of the ship maintenance create environments in which sailors can slip and fall over board or get injured. Shipboard evolutions that result in sailors being exposed to the environment outside of the ship pose potential injuries. Heavy seas can create imbalances in which a sailor fails to hook an approaching helicopter correctly that can cause an improper landing leading to injuries.

Fine motor skills can be interrupted by MIIs causing mechanical failures on equipment while performing maintenance or operating procedures. Numerous maintenance procedures occur onboard ships where one false movement created from losing balance can create great physical harm. As people trip and slip from MIIs, they can encounter machines and equipment around them that cause bodily harm. The potential for injury affects manpower because if a sailor with a critical mission becomes injured, a backup is then needed.

3. Human Factors Engineering

Human factors engineering (HFE) attempts to account for human error and limitations. Since human limitations are static in terms of physiology and anthropometry, ship and system design must consider these limitations. In this case, HFE needs to account for the limitations humans have in heavy sea environments.

MIIs are a fact of life in heavy seas. If it is possible to understand the human limitations and physics behind them and how they are caused physiologically, HFE can use that information to inform ship designs that mitigate tripping mishaps. In the same way that cars have shock absorbers to decrease jolt from potholes and bumps in the road, ships may have the potential to be designed to better absorb the impacts of waves, which create MIIs. Machines and certain pieces of equipment need built-in flexibility to account for potential mistakes made from trips caused by harsh conditions. As systems become more complex, HFE needs to ensure that systems are better equipped to handle MIIs. Woods and Hollnagel (2006) defined the concept of resilience as to how well a system recovers from a disruption. MIIs are the kinds of disruptions presented in this thesis that human factors engineers need to consider early in ship design if the goal is to achieve reduced manning on future ships.

H. PROPOSED MII MODEL

This thesis proposes to contribute an MII Forecasting Model based on the findings of the historical perspective and experimental data. The independent variables consist of two categories. The first are environmental conditions consisting of level of acceleration, and duration of time or period. For example, ship designers may design ships based on a given probability of MII occurrence considering maximum accelerations and periods caused by waves of different sea states. The second category consists of the individual differences in the Sharpened Romberg scores and tipping coefficient. For example, ship designers and manpower personnel can design ships that account for 95% of the average Sharpened Romberg scores and individual tipping coefficients. Personnel with abnormal balance abilities and heights would not need to be incorporated in ship design since they would not be selected for service in the first place. However, balance abilities and an

individual's tipping coefficient would dictate what limits of ship motion give acceptable MII occurrence risk. The development of a quantitative model may help systems engineers and ship designers forecast MIIs on future ship platforms and develop MII requirements. The next chapter describes the methods used in the experiment and the analysis used to develop the MII Forecasting Model.

III. METHODS

A. METHOD OVERVIEW

The objective of the experiment was to determine what levels of motion and period lead to MIIs. The experimental design had four independent variables and one response variable. Two of the independent variables were individual continuous variables, sway axis acceleration and period. These variables were manipulated using a Motion Based Platform to simulate a typical ship deck motion. The other two independent and continuous variables were Sharpened Romberg scores and an individual's tipping coefficient. The dependent variable (DV) was MIIs defined as the clear movement of at least one of the heels or a step to maintain postural equilibrium. This methodology sought to capture the variability that exists in humans involving lateral linear motion (period and acceleration), as well as individual differences of natural balance capabilities and tipping coefficient.

B. SAMPLE

The sampling procedure included recruiting volunteers who work at NSWC Panama City (NSWC PC) by email and face-to-face invitations. The sample consisted of 21 subjects that include military and civilian men and women of varying age and sea time experience; 16 were men and five were women. The range of sea time was 0 to 25 years. The mean time at sea was 2.3 years. The subjects' ages were not recorded.

C. MATERIAL

1. Hexapod Motion Base (MOOG Model 6DOF5000)

The Hexapod motion base is a 10x10 foot, six degrees of freedom (DoF) motion platform capable of emulating heave, pitch, roll, yaw, surge, and sway of ships steaming in in the ocean (Broadstreet, 2013). People or devices can be placed on a top plate affixed to the platform. The motion platform has a payload of 5,500 lbs. with a maximum sway displacement of 0.46 meters and a maximum sway acceleration of 6.5 dm/s^2 when the motion platform began acceleration from the center neutral position (Turret Test Systems,

2013). The sway displacement was the major factor limiting the ability to produce sway motion exceeding an acceleration value of 0.28 G over 1.5 seconds. Figure 4 shows an example of a motion base similar to the one used in this study.

Figure 4. Motion Base System (From Turret Test Systems, 2013)

2. Motion Capture Garment

Each subject donned a full body motion capture suit embedded with approximately 70 reflective markers. The garment consisted of neoprene stretchable fabric that allowed the full range of human motion. The reflective markers were acquired by a Vicon motion capture system consisting of seven infrared cameras. The video data will be used to analyze joint angles and limb movements, which will be reported separately. Analysis Tools

Microsoft Excel was used to compile and organize the data collected from the experiment. JMP version 10 was used to perform multiple and logistical regression. Autodesk Maya 2012 was used to extract FBX files from the motion capture software system to obtain the individual stance widths to calculate Graham’s tipping coefficient.

3. Equipment

The following equipment was used during the course of this experiment.

- Laptop computer
- Hexapod motion base (MOOG Model 6DOF5000)
- Safety harness
- Vicon motion video capture system
- Motion capture suit
- Stop watch
- 3M safety walk tape

D. EXPERIMENTAL DESIGN

In ship terminology, the three linear axes of motion on a ship are known as heave, surge, and sway and the primary axes rotations are pitch, roll, and yaw. The experiment included trials of sway, sway + roll, sway + pitch, and sway + pitch + roll. This thesis reported sway acceleration only and the other combinations will be reported separately. Each subject experienced the same order and sequence of 32 sway trials as shown in Table 2.

Table 2. Experimental Trial Sequence

Trial #	**Acceleration (g)**	**Acceleration (dm/s/s)**	**Period (seconds)**
1	0.16	15.68	1
2	0.20	19.60	1
3	0.24	23.52	1
4	0.28	27.55	1
5	0.16	15.68	1.5
6	0.20	19.60	1.5
7	0.24	23.52	1.5
8	0.28	27.55	1.5
9	0.16	15.68	1.75
10	0.20	19.60	1.75
11	0.24	23.52	1.75
12	0.28	27.55	1.5
13	0.12	11.76	2
14	0.14	13.72	2
15	0.16	15.68	2
16	0.18	17.64	2
17	0.16	15.68	1
18	0.2	19.60	1
19	0.24	23.52	1
20	0.28	27.55	1
21	0.16	15.68	1.5
22	0.20	19.60	1.5
23	0.24	23.52	1.5
24	0.28	27.55	1.5
25	0.16	15.68	1.75
26	0.20	19.60	1.75
27	0.24	23.52	1.75
28	0.28	27.55	1.5
29	0.12	11.76	2
30	0.14	13.72	2
31	0.16	15.68	2
32	0.18	17.64	2

Of the 14 different conditions, some were repeated twice while others were only repeated once. G forces were converted and shown in decimeters/second/second to help interpret logistic regression analysis. To prevent the subject from being able to predict which direction of motion would occur, an unpredictable sequence of left and right acceleration was generated.

E. DATA COLLECTION/PROCEDURES

Ms. Amanda Bandstra, a member of the NSWC-PC Human Factors Group, recruited participants. Human Systems Integration Team Lead, Eric Pierce, managed the data collection team. Human Systems Integration Team Safety Observers Jeff Kiser and Ashley Catlin were present to assist subjects with the equipment, as well as data collection.

Each volunteer was asked to report to the designated building containing the motion platform at his appointed time. After an initial health screening by questionnaire to disqualify anyone with health issues, participants were fully informed about the objectives, procedures, risks, and benefits of the study. Examples of the pre and post study questionnaires, the recruiting script, and the informed consent sheet are located in appendices A, B, C, and D, respectively.

Subjects donned the motion capture garment, helmet, and kneepads with the help of the motion capture team followed by a brief period of calibration. Figure 5 shows an example of a person donned in the motion capture garment standing on the motion base.

Figure 5. Subject Standing on Motion Base

The motion capture suite is used as a backup to determine MII occurrence, as well as analyzing joint angles and motion. The participant was asked by the administer to undergo a Sharpened Romberg balance test three times, before, midway, and after the motion exposures. Each test involved standing heel-to-toe with arms crossed and eyes closed for 60 seconds or until a loss of balance occurred. The Motion Sickness Assessment Questionnaire (MSAQ) was administered as part of the pre-test. Once completed, the participant was guided to the desired standing position on the motion platform where they were strapped to a safety harness. The safety harness had the ability to be lowered and raised to achieve normal standing center of gravity. Once hooked in, a period of one minute of normal standing occurred to obtain a baseline before the actual trials began.

Trials consisted of various ascending combinations of sway and periods in a predetermined simulator input pulse order. Each subject was administered a total of 32 trials under the prescribed pattern located in Table 1. A five-minute break was given in the middle of the data collection period to control for fatigue.

After an approximate 60-minute period of data collection, the participant was dismounted from the safety harness and helped off the motion platform. He then doffed the motion garment, helmet, and kneepads. During the post session, a Sharpened

Romberg test was administered three more times. After the session, the post questionnaire was administered. The participant was seated until any symptoms had subsided and was then released.

F. VARIABLES

1. Response Variable

The response variable selected is a binary event, the occurrence of a MII, which is the movement of a foot or heal or a visible step to maintain postural balance. The researcher observed all trials and noted trials on which a MII occurred. MIIs were selected as the response variable because they are observable and quantifiable.

2. Independent Variables

The independent variables selected for multiple and logistic regressions were derived from the literature review along with research related to human postural balance. Acceleration values were initially determined from Graham's recommendations—0.08 G's to 0.16 G's, Figure 2. However, as no MIIs were observed at these levels during the pre-trials, acceleration values were increased to the allowable limits of the Hexapod motion base to ensure the best chance of MII occurrence. One cycle of a sine wave was used for each sway event. For computing purposes, G forces of acceleration were converted to decimeters/second/second. Period of the sine wave cycle was specified in seconds. Based on the pre-trials and the maximum periods allowed by the motion base, seven levels of sway and four levels of period were derived.

Acceleration values (dm/s^2) were: 11.72, 13.72, 15.68, 17.64, 19.60, 23.52, and 27.55

Period values (sec) were: 1.0, 1.50, 1.75, and 2.0

The combinations of sway and period were constrained by the limitations of the motion base. Only 14 unique conditions could be produced. Some were replicated to give a total of 32 trials, Table 1.

The independent variables are as follows.

- Lateral (Sway) acceleration (dm/s^2)
- Period (seconds)
- Graham's tipping coefficient (cm)
  - Assumption of average female COG is 0.543*height and the average male COG is 0.56*height (Elert, 2006).
- Sharpened Romberg Score (seconds)

3. Control Variables

Participants were required to wear tennis shoes or running shoes to limit friction variability. The subjects stood on the 3M safety walk, which is a gritty surface providing high friction. For each trial, participants faced forward at the center of the motion platform, straddling the center of the platform. Participants were told to stand in their normal stance and return to that position after each trial. Tape was used for all participants to mark the position of their feet, which enabled them to regain the initial stance width. This procedure was implemented to limit the tipping coefficient variability. For each trial, participant's eyes were open and no cognitive tasks or other workload was imposed. Participants were screened for medical related issues that would impair their balance ability to include any injuries related to balance or lost limbs. Participants who had consumed alcohol within 24 hours or had poor recent sleeping habits also were excluded to mitigate the potential for false positives due to their physiological state.

4. Analysis

The analysis of the data was conducted by multiple and logistic regression. Multiple regression techniques distinguished the best models using acceleration and period variables while logistic regression addressed any significance of individual difference variables. Multiple regression used acceleration and period as predictors. The regression equation gives probabilities of MII incidents given stated acceleration and period values. The regression equation enables quantitative analysis of the significance of period. Logistic regression used acceleration, period, tipping coefficient, and Sharpened Romberg scores as predictors. Logistic regression determined if adding individual differences from Sharpened Romberg scores and tipping coefficients were significant to

this research. The models used the multiple regression function in Equation 3 and the logistic function in Equation 4.

$$MII = \beta_0 + \beta_1 X_1 ... + \beta_i X_i$$

Equation 3. MII Multiple Regression Equation

$$MII = \frac{e^{(\beta_0 + \beta_1 X)}}{1 + e^{(\beta_0 + \beta_1 X)}}$$

Equation 4. MII Logistic Regression Equation

Graphs were used to help understand how acceleration and period interact. Microsoft Excel can produce 2-dimensional graphs showing the relationship of these predictors in regards to MIIs to help distinguish which models make better sense. 3-dimensional graphs can show the similarities between the experimental data and the best regression models selected to help ascertain if the models are behaving in a way that represents the raw data.

Also, when comparing the results of this study to the Graham's Tipping Equation, the equations in Equations 5 and 6 were used.

$$-\ddot{D}_2 > \frac{l}{h} g \text{ (tip to port)}$$

Equation 5. Simplified Graham Tipping Equation (tipping to port)

$$\ddot{D}_2 > \frac{l}{h} g \text{ (tip to starboard)}$$

Equation 6. Simplified Graham Tipping Equation (tipping to starboard)

Equations 5 and 6 are simplified forms of Equations 1 and 2 that remove longitudinal acceleration and roll. Comparing MII incidents from the experiment to what the equations predict make it possible to assess the validity of Graham's Tipping Equation and confirm Crossland's assessment that Graham's equations over-predict the probability of MIIs.

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IV. RESULTS

A. OVERVIEW

This research tested the hypothesis that MIIs would be influenced by sway acceleration, period, tipping coefficient, and Sharpened Romberg scores. The experiment included trials of sway, sway + roll, sway + pitch, and sway + pitch + roll. This thesis reported sway acceleration only, while the other combinations were reported separately. During the experiment, a total of 21 subjects were exposed to 15 combinations of a range of lateral (sway) accelerations for a range of periods. Some of the combinations were repeated resulting in 32 trials for each subject. A total of 672 nominal raw data points were collected. Multiple regression and logistic regression were the major methods of analysis. For multiple regression to be performed, each experimental condition needed to be averaged over each subject to obtain ratio data. Multiple regression distinguished the best models using acceleration and period as predictor variables while logistic regression addressed any significance of two additional variables that reflect individual difference, tipping coefficient, and Sharpened Romberg scores. The key of independent variables used throughout the results is shown in Table 3.

Table 3. Independent Variable Key

X_1	=	Acceleration
X_2	=	Period
X_3	=	Period*Period
X_4	=	Acceleration*Period
X_5	=	Tipping Coefficient
X_6	=	Sharpened Romberg

B. MII MULTIPLE REGRESSION ANALYSIS

Data were entered into JMP Version 10.0 for analysis using the multiple regression procedure. The first step was to run multiple regression models using combinations of acceleration and period as predictors to help determine the most significant predictors and the best-fit models. The number of parameters, error sum of squares, F ratio, P value, R^2, and R^2 adjusted ($R^2_{a,p}$) of each of the models are shown in

Table 4, which consists of six different models labeled 1 through 6. Model 2 shows period to be an insignificant predictor but when added to models containing acceleration, the models improve.

Table 4. Multiple Regression Analysis

Model	Variables	p	SSE_p	F Ratio	P Value	R^2	$R^2_{a,p}$
1	X_1	2	1.03	30.43	0.0001	0.500	0.487
2	X_2	2	2.07	0.18	0.6700	0.006	0.027
3	$X_1 + X_2$	3	0.56	39.03	0.0001	0.729	0.710
4	$X_1 + X_2 + X_3$	4	0.49	30.56	0.0001	0.770	0.741
5	$X_1 + X_2 + X_4$	4	0.35	45.88	0.0001	0.830	0.813
6	$X_1 + X_2 + X3 + X_4$	5	0.35	33.18	0.0001	0.831	0.806

Figure 6 is a graph that shows each multiple regression model's R^2 adjusted values plotted against the number of parameters. This figure accounts for model complexity because R^2 values increase as each variable is added to a model, whether significant or not. R^2 adjusted accounts for the added complexity. Inspection of the graph reveals that Models 4 and 5 are conclusively the best statistical models based on the number of parameters and R^2 adjusted values. They include the period squared effect and the interaction between acceleration and period, respectively. Both models' parameter estimates are reported in Table 5.

To assess the quality of Model 4, the confidence intervals of the betas and the residuals were analyzed. Confidence intervals containing 0 indicate a poor predictor. Also, one of the fundamental assumptions of regression is that the variance of the residuals is constant for all values of X. Table 5 shows the parameter estimates and 95% confidence intervals for Models 4 and 5. Since none of the confidence intervals contains 0 in either models, each beta is a worthy predictor and hence the model is attractive.

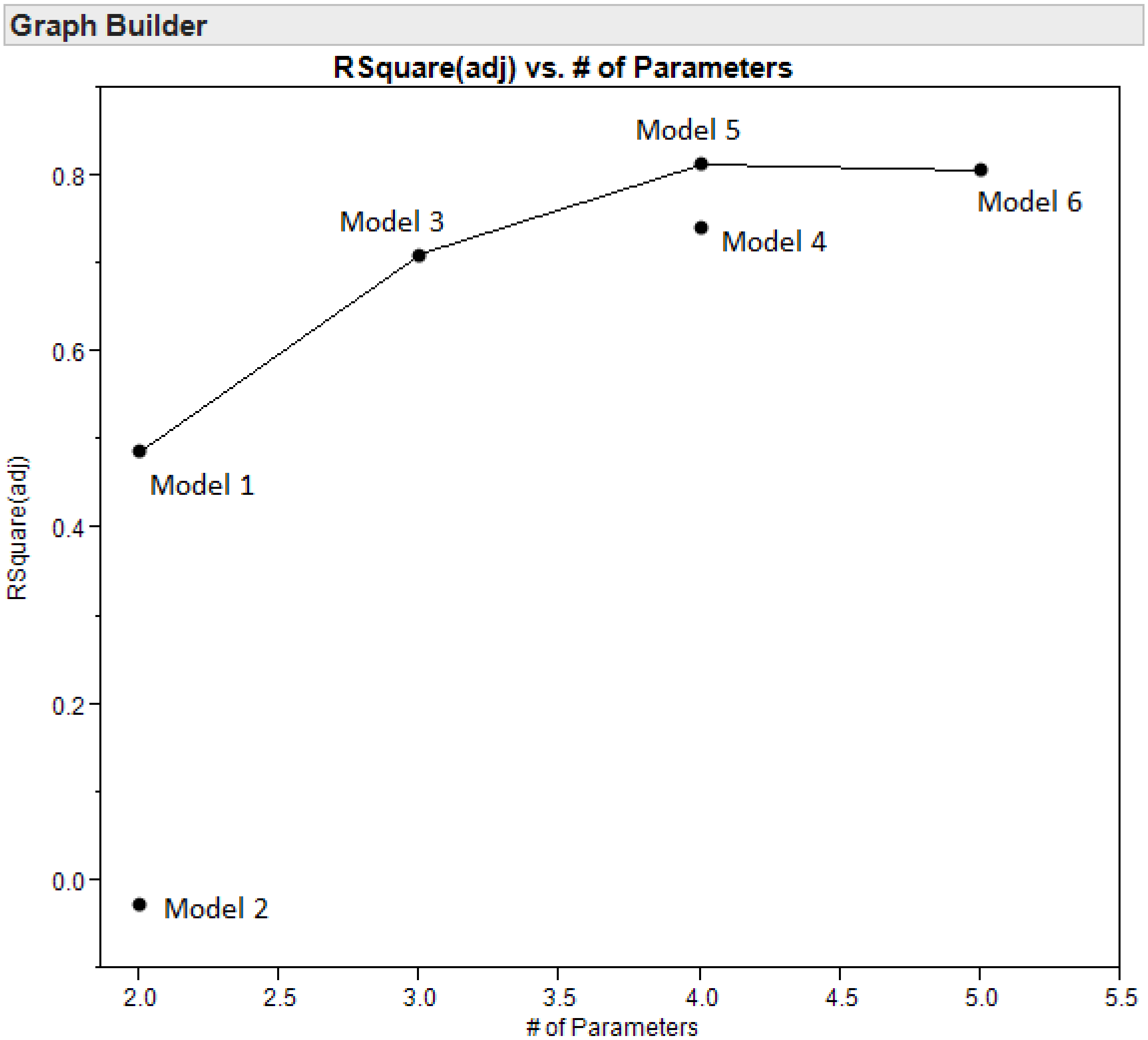


Figure 6. Variables Selection Criteria Plot

Parameter Estimates Model 4

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-1.298247	0.162026	-8.01	<.0001*	-1.630141	-0.966352
Acceleration	0.0511151	0.004577	11.17	<.0001*	0.0417386	0.0604915
Period	0.4358966	0.063262	6.89	<.0001*	0.3063113	0.5654819
(Period-1.54688)*(Acceleration-19.845)	0.0518962	0.012637	4.11	0.0003*	0.0260108	0.0777817

Parameter Estimates Model 5

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-0.888998	0.249354	-3.57	0.0013*	-1.399777	-0.378219
Acceleration	0.0438153	0.006132	7.15	<.0001*	0.0312555	0.0563751
Period	0.2781495	0.086214	3.23	0.0032*	0.101549	0.45475
(Period-1.54688)*(Period-1.54688)	-0.486661	0.231497	-2.10	0.0447*	-0.960861	-0.012461

Table 5. Models 4 and 5 Parameter Estimates

1. Model 4

Figure 7 shows the observed data and the fits of quadratic Model 4 to the data, which is the first acceptable model from the regression analysis. Dots represent the actual raw data from the experiment and the lines what the model predicts for the given accelerations.

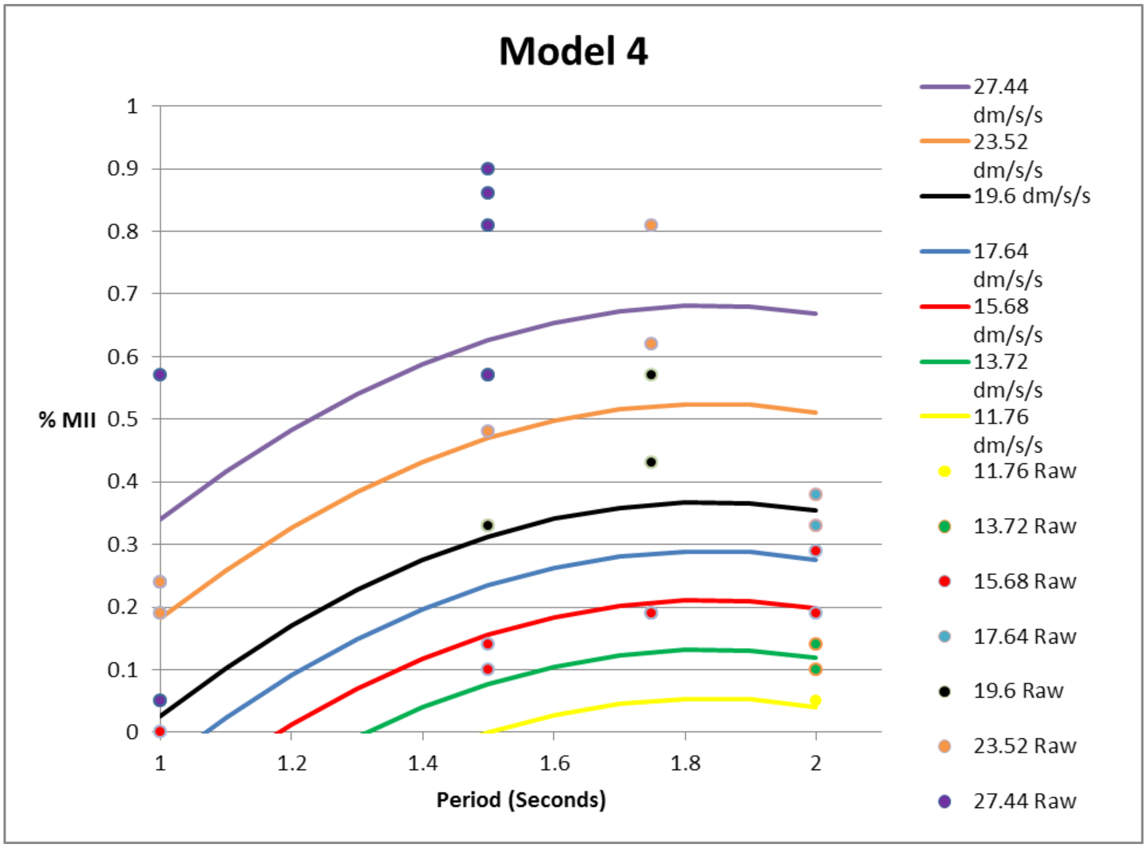
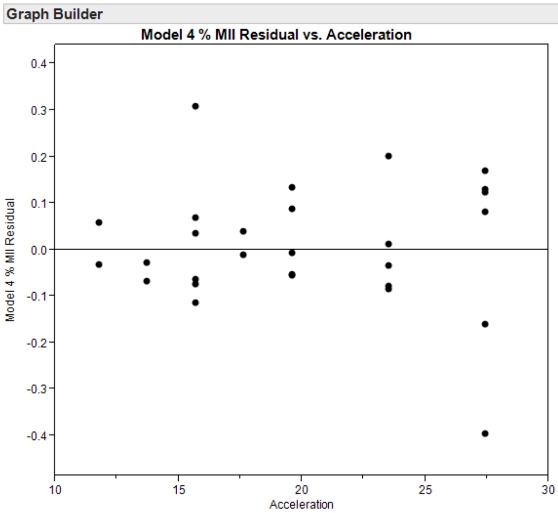


Figure 7. Model 4 Multiple Regression Graph

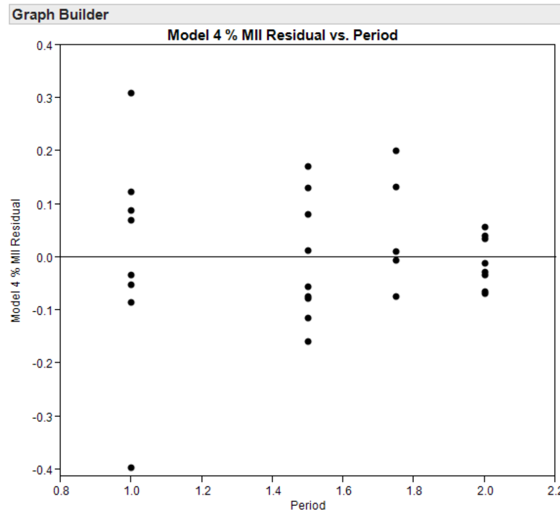
As period and acceleration values approaches zero, the predicted number of MIIs goes to zero; this seems reasonable. Holding period constant, MIIs increase as acceleration increases (as shown in Figure 7). Holding acceleration constant, MIIs increase as period increases and reaches peak values between 1.55 seconds and 1.8 seconds because after enough time passes, if an MII has not been achieved, it is less likely that further exposure time is going to induce an MII. Figure 6 reveals that Model 4 identifies a potential peak period value around 1.8 seconds per any given acceleration where MIIs are maximized.

Figure 8a shows the Model 4 residual plot for acceleration. The residuals (e(yi)) appear constant and evenly scattered around e(yi) = 0 for all values of X and validate the assumption of constant variance. Figure 8b shows the Model 4 residual plot for period. As seen in Figure 8a and 8b, the residuals appear to be fairly constant. Taking into account the confidence interval test and the residual validation, Model 4 appears to be a good model.



(a)

Model 4 MII Residual vs. Acceleration



(b)|

Model 4 MII Residual vs. Period

Figure 8. Model 4 MII Residual Plots

2. Model 5

Figure 9 shows the linear fit from Model 5. As the period increases, so do the incidences of MIIs. As acceleration levels increase so does the incidences of MIIs. Unlike Model 4, Model 5 shows the absence of a peak in MII incident, which indicates that as period increases, MII incidents increase at the same rate regardless of acceleration values.

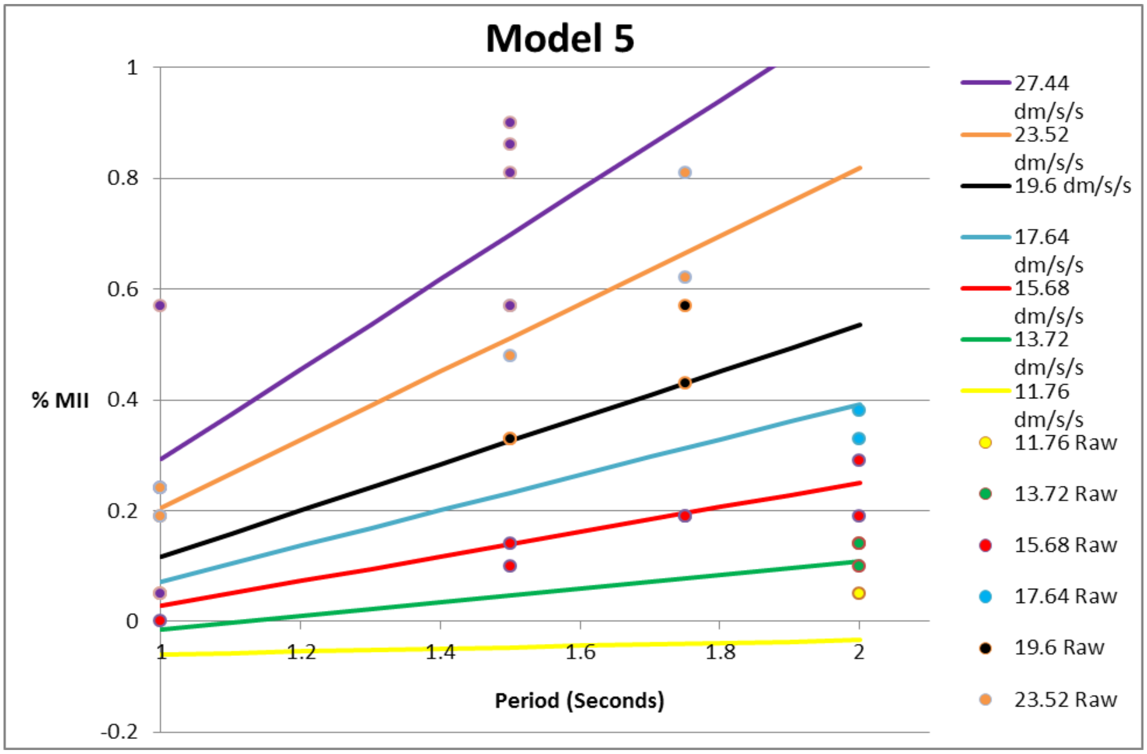
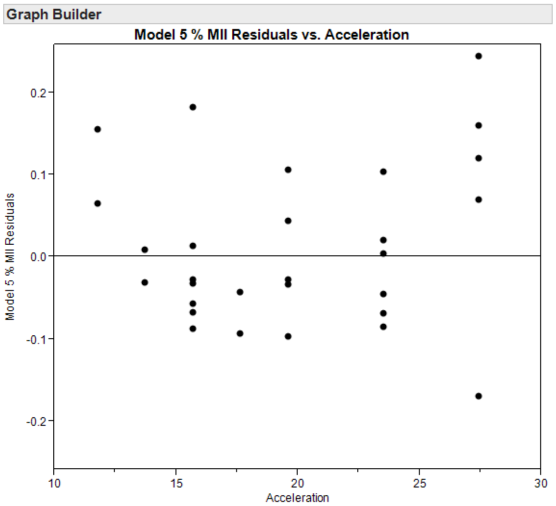
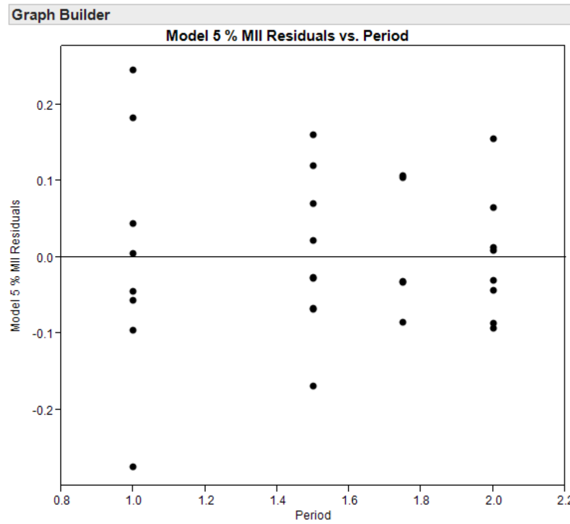


Figure 9. Model 5 Multiple Regression Graph

Figures 10a and 10b show the Model 5 residual plot for acceleration. The residuals do not appear to be evenly scattered in Figure 10a. They have a clear curved pattern. The residuals appear to be evenly scattered in 10b. The constant variance assumption seems to be broken with interaction Model 5 due to Figure 10a despite constant variance holding when it comes to period. Failure of constant variance shown in Figure 10a reveals that model is not so great. Model 4 is the more appropriate model to use for MII forecasting.



(a)
Model 5 MII Residual vs. Acceleration



(b)
Model 5 MII Residual vs. Period

Figure 10. Model 5 MII Residual Plots

3. Model Comparison

Finally, to compare models 4 and 5, and show that they both realistically captured the MII data, 3D surface graphs were constructed and compared to a raw data plot. Figure 11 presents the raw data plot and was produced by interpolation and extrapolation from averaging to filling in some missing data cells due to mechanism limitations of the motion base, which was needed so that Excel would not plot 0's from an incomplete matrix. Figures 12 and 13 are surface plots from models 4 and 5, respectively, and are used to visually compare to the raw data plot. Models 4 and 5 compare well visually to the raw data. It would seem reasonable to conclude that both models are able to explain the data. Model 5 is a better fit than Model 4 (R^2=0.83 and R^2=0.77, respectively). However, Model 4 may be more realistic. When conceptualizing extreme periods at low acceleration, MIIs would probably not increase over time. Model 5 in Figure 13 clearly shows the linear increase in MIIs, which contrasts slightly to the raw data that shows a peak and a leveling off in MIIs. Figure 12 gives a better representation of a peak occurring, which provides more evidence that Model 4 with the period2 term is the most appropriate model for MII forecasting.

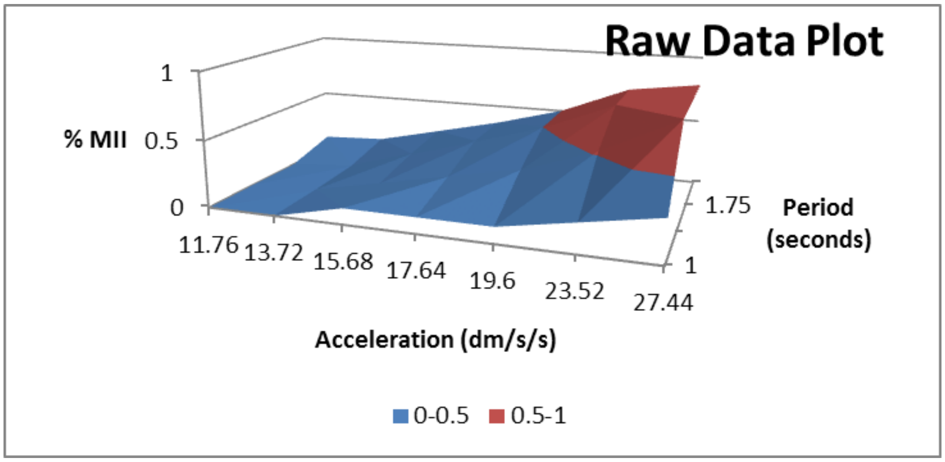


Figure 11. Raw Data Plot

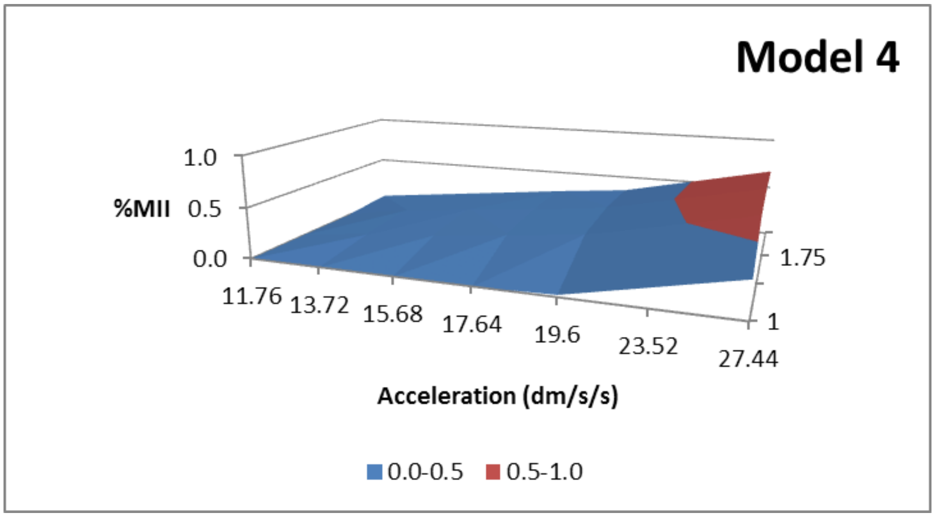


Figure 12. Model 4 Multiple Regression Graph

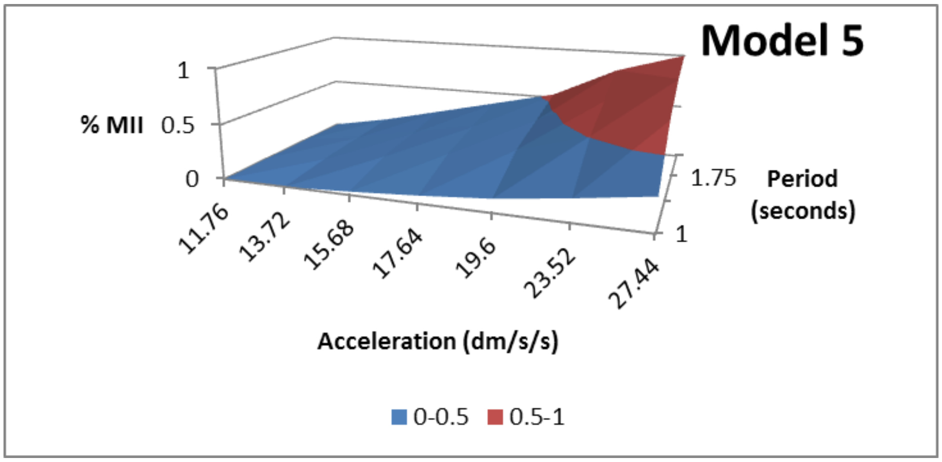


Figure 13. Model 5 Multiple Regression Graph

C. MII LOGISTIC REGRESSION ANALYSIS

The next step consisted of fitting logistic regression models with the binary MII data as the response variable. Refer to equation 6 for the logistic equation. The purpose was to determine if measures of individual differences improved the best fit models derived using multiple regression. The third Sharpened Romberg scores during pre-motion exposure were used because they were the most significant and accounted for practice effects. Fourteen different models using a variety of different combinations of independent variables were performed. Predictor combinations from multiple regression were included in logistic regression to validate the best models by concurrence between analyses. Refer to Table 3 for the key to the predictors. Table 6 lists the predictors, number of parameters, the χ^2 value, the χ^2 p-value, and R^2 of each model designated by a letter. A total of five independent variables were used to derive the most complex models signified as Model J and Model N.

Table 6. Logistic Regression Model Selection Criteria

Model	Variables	p	χ^2	$P(\chi^2)$	$R^2(U)$
A	X_1	2	100.95	0.0001	0.117
B	X_2	2	1.17	0.2800	0.001
C	X_5	2	1.37	0.2419	0.002
D	X_6	2	5.51	0.0189	0.006
E	X_1, X_2	3	154.64	0.0001	0.179
F	X_1, X_6	3	107.47	0.0001	0.124
G	X_1, X_2, X_3	4	161.74	0.0001	0.187
H	X_1, X_2, X_3, X_5	5	163.56	0.0001	0.189
I	X_1, X_2, X_3, X_6	5	168.90	0.0001	0.195
J	X_1, X_2, X_3, X_5, X_6	6	173.06	0.0001	0.200
K	X_1, X_2, X_4	4	169.79	0.0001	0.196
L	X_1, X_2, X_4, X_5	5	171.62	0.0001	0.198
M	X_1, X_2, X_4, X_6	5	177.08	0.0001	0.204
N	X_1, X_2, X_4, X_5, X_6	6	181.32	0.0001	0.209

Logistic results align with multiple regression results to indicate that period is not statistically significant as a single predictor in Model B but it is significant in combination with others. Sharpened Romberg (X_6) appears to be statistically significant as a single predictor in Model D and stays significant when added into more complex models. Significant improvements of the fit occurred when all but the tipping (X_5) were added to the models. Tipping coefficient (X_5) fails to be statistically significant as an individual predictor and only becomes significant when added into more complex models (J and N). Figure 14, just like Figure 6, helps determine which models are the best by the most appropriate variable selection. The number of parameters is taken into account as extra variables are added. Based on Figure 14, Models M and N are the best statistical models. When it comes to model selection, Model M is the preferred model because of the added complexity model N. Also, model N contains the tipping coefficient variable that proved to be insignificant as a sole predictor in Model C. By selecting Model M, credibility is given to Sharpened Romberg as a useful and worthwhile predictor.

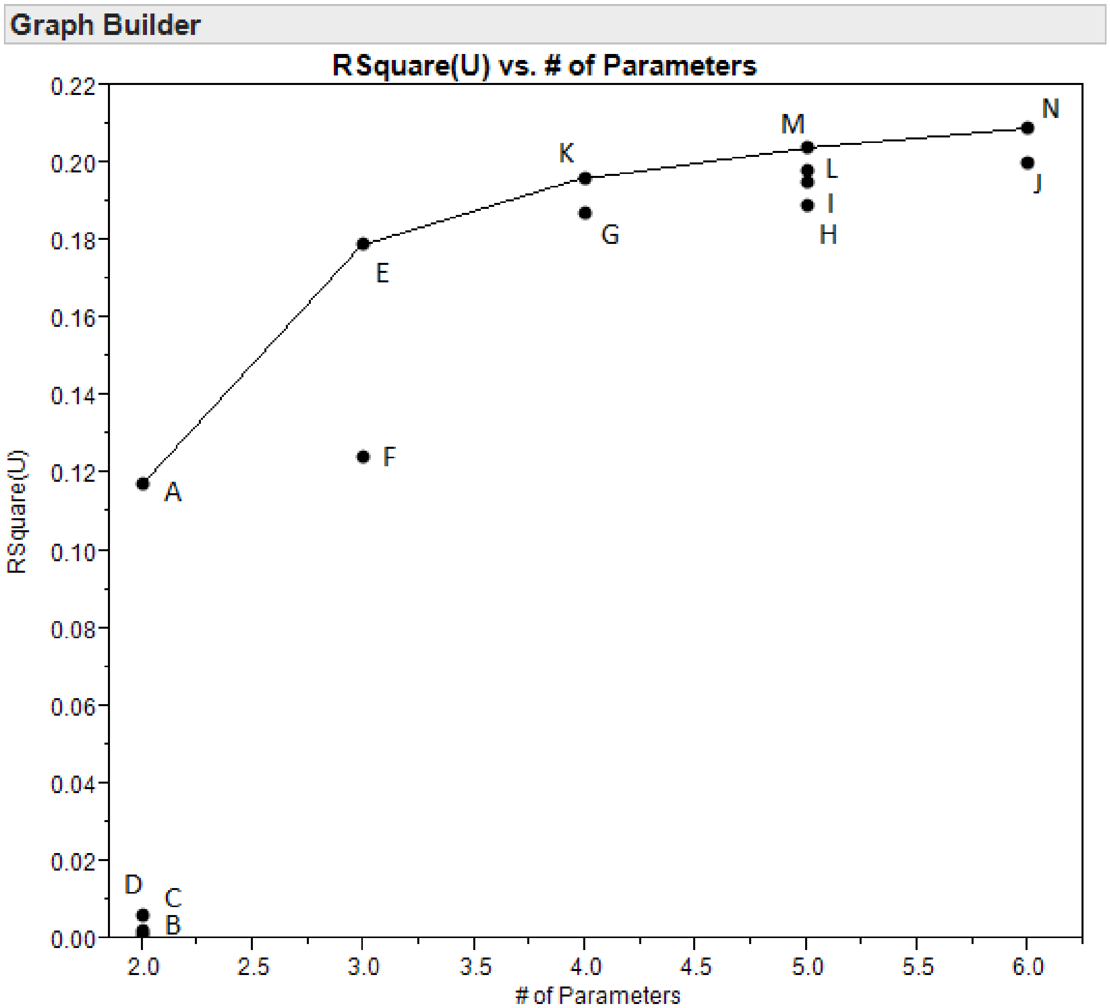


Figure 14. Variables Selection Criteria Plot

D. GRAHAM'S TIPPING EQUATION

Acceleration values and each subject's tipping coefficient for each trial were inserted into Equation 6 to determine whether Graham's equation predicted a MII or not. The predictions were then compared against the actual observations. Of the 672 observations, Graham's Tipping Equation properly predicted the outcome 60.4% of the time. Graham's equation under-predicted 6.9% of the time and over-predicted 33.2% of the time.

Of the 672 conditions, Graham's Tipping Equation predicted that at least 412 would have a MII incident giving a predicted MII rate of 61.3% for this study. The actual data show that only 232 MII incidents resulted in an actual MII rate of 34.5 percent. These findings clearly show that Graham's Tipping Equation over-predicts MIIs.

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V. DISCUSSION

A. RESEARCH QUESTION ONE

The question of whether period has a relationship with MIIs is partially supported. Table 3 shows Model 2 with period as an individual predictor. The resulting fit is a poor model ($P < 0.67$). However, when period is added into models containing acceleration, period is significant and it improves the overall fit of the model. For example, Table 5 shows period is significant in Models 4 and 5 ($P < 0.0031$ and $P < 0.0001$, respectively). One explanation for this finding is that a MII has a higher probability of occurrence if a human endures acceleration over a longer period of time than a shorter one. In addition, a specific frequency may occur where the likelihood of MIIs is maximized instead of the idea that the MII rate will approach 100% as period keeps increasing, which is similar to the findings of motion sickness when specific oscillation ranges cause the greatest incident of motion sickness. Whereas, higher or lower frequency oscillations decreased the rate of motion sickness (McCauley et al., 1976).

B. RESEARCH QUESTION TWO

The question of whether a person's tipping coefficient has a relationship with MIIs was not supported. Logistic regression showed that tipping coefficient was not significant as a single predictor ($P < 0.24$). Table 1 shows that tipping coefficient becomes significant only when added to models J and N, which contained all other predictors ($P < 0.04$). This significance is highly suspect due to potential multicollinearity and the high complexity of the model. One explanation for this finding is that humans may tend to become accustomed to their own type of stance width in relation to their center of gravity. Humans may compensate accordingly for environmental motions to mitigate potential MIIs. If a person has an undesirable tipping coefficient, better abilities might be adapted and developed to compensate for motion disturbance.

C. RESEARCH QUESTION THREE

The question of whether a person's balance ability has a relationship with MIIs is supported. In Table 6, Sharpened Romberg scores appear to be statistically significant as a single predictor (Model D) and stay significant when added into more complex models. Balance ability alone has a statistically significant relationship with MII but is much weaker in models that include acceleration. These findings support the conclusion that people who score better on Sharpened Romberg scores generally have fewer MIIs than people who score poorly.

After adding Sharpened Romberg to the predictor combinations from Models 4 and 5 from multiple regression, logistic Model I and M result. Models 4 and 5 were examined because they were defined as the best fit and statistically significant models. Models I and M show significant positive increases in chi squared values from the whole model test, which shows that models with the Sharpened Romberg predictor are better than those without it. One explanation for this finding is a MII is less likely to occur if a human has better postural balance abilities over a person with poorer balance. Sharpened Romberg test seems to have a significant effect on the likelihood of MIIs and is worthwhile to add to the models. Further research should incorporate balance abilities as a potential factor in MII forecasting.

These results support the argument that HSI should consider Sharpened Romberg scores as an ability in the personnel domain. The potential value for selecting sailors with better balance over others could prove to decrease incidents and increase performance related to HSI over time.

D. RESEARCH QUESTION FOUR

The question of whether it is possible to use laboratory data to derive a model that predicts the relative likelihood of MIIs is supported. Multiple regression Models 4 and 5 had the highest statistical significance and best fit. The predictors in Model 4 were acceleration, period, and period^2 resulting in a quadratic. Model 5 was an interaction model with acceleration, period, and period*acceleration as predictors. They were further examined by developing graphs for comparison to determine whether both models are useful or not.

Model 4 fits the idea that a maximum period value will exist where no further exposure time to the given acceleration value will incur more frequent MIIs. Model 5 does not. For example, if a peak 50% chance of incurring a MII at an acceleration value of .24 G's over 1.5 seconds were possible, it would not' matter if the period was changed to 5 seconds or 10 seconds. If anything, the percentage would potentially decrease from 50% due to the idea that a person would have time to adjust to the acceleration and prepare for a sudden stop in motion, which would help prevent a MII from occurring. For this reason, Model 4 was selected for MII forecasting. Ship designers can use the simplicity of Model 4 to create ships that can behave within the acceleration and period boundaries for desired MII risk.

The finding that period is significant is important because it does not appear in previous research. Period has an important role to play with sea going vessels due to the dynamic motions of waves and ocean current. Model 4 predicts that 1.55 could be a potential spot where MIIs are maximized. Future research covering a greater range of acceleration and period needs to be conducted to validate this potential spot and to understand the greatest MII risk levels. Designing ships with the understanding that a certain period incurs the most MII risk can contribute to operational risk management in naval operations.

Logistic regression was needed to determine if individual differences played a role in MII occurrence. Model M was the best statistical model, which incorporated the variables X_1, X_2, X_4, X_6. Period, acceleration, and Sharpened Romberg scores were all significant. Tipping coefficient was not a significant predictor. It is recommended that Model M be used for incorporating individual differences over the other logistical model combinations analyzed in this thesis. Balance abilities seem to play a role in the occurrence of MIIs in the experiment but the logistic model does not account for the possibility of a MII peak and Model 4 does. Also, since multiple regression Model 4 is much simpler than logistic regression Model M, Model 4 is the final recommended model for MII forecasting. This thesis study feels the information from just acceleration and period gives the necessary data needed to predict MIIs best.

E. RESEARCH QUESTION FIVE

This study supports the premise that Graham’s Tipping Equation over-predicts MIIs. This finding is consistent with previous research findings that Graham’s Tipping Equation over-predicted MII occurrence (Crossland & Lloyd 1993). One explanation for this finding in the research was the idea that humans ’are not rigid stick figures that tip over without any self-correcting mechanisms. Humans compensate and adjust their balance in conditions of varying motion. Also, given a particular task, a person’s tipping coefficient can change, such as when carrying a large heavy object. Future investigations should focus on the environmental factors affecting the sailor and the specific tasks being performed versus his natural physical anthropometrics. However, this study does show that individual physiological differences, such as natural balance ability, play a role in MII prediction.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

MIIs are an example of human performance degradation that can cause negative effects like human injury, performance decrements, or equipment damage. MIIs should be considered when calculating maintenance and lifecycle costs of military systems, and for their effect on mission readiness, and effectiveness. The literature review discusses manpower, human factors engineering, environmental safety and occupational health and how they are interrelated when attempting to mitigate MIIs through ship design. A more effective ship design through HFE will lower MIIs, reduce the need for more manpower due to injury and maintenance, and create a more environmentally safe and healthy environment in which to work.

This thesis reached its four objectives. The first objective was to assess how period and acceleration affected the occurrence of MIIs, which was accomplished by developing an experiment that produced data that could be explained through multiple regression. The second was to assess the relationship of motion and individual traits on MII occurrence. These objectives were accomplished by the quantitative analysis and comparison through logistical regression. The third objective was to develop and assess a model using appropriate predictors to forecast MIIs, which was accomplished by the statistical and rational comparison of multiple logistic regression models. The final objective was to compare the experimental results with Graham's Tipping model that was completed by using acceleration values from the experiment in Graham's Tipping Equation and seeing whether the MII prediction matched the observations in the simulator, which it did not.

B. RECOMMENDATIONS

HSI is important for the future of ship design in relation to task performance. The study of how the physical environment impacts human performance is necessary to ensuring maximum mission readiness. Budget constraints and rising health costs continue to have an effect on defense spending; therefore, it is important to develop ship platforms that minimize human performance degradation.

A major finding from this study was the significance of period on MIIs. Previous research had focused only on the level of acceleration and had not mentioned period as a contributing factor to MII occurrence. It is recommended that period be taken into account for ship design. Sharpened Romberg scores as a valid predictor was also a significant finding. Recruiters should incorporate balance abilities into the selection process for ships or positions highly prone to MIIs. If sailors with poor natural balance are put in positions of handling small boats or helicopter, an injury is more likely to occur because they are more likely to exhibit a MII. Another finding was the failure to create MIIs in the simulator at specified acceleration levels in Figure 3. The figure suggests serious to severe MIIs incidents at 0.12 G's (11.76 dm/s2), which was not found. Accelerations of 0.16 G (15.68 dm/s2) were required before consistent MIIs were observed. The experiment found that much greater accelerations were needed to create MIIs than were predicted in earlier research.

The modeling of relationships between potential predictors and MIIs continues to be a challenging field. One major challenge is the growing number of potential variables and the interactions they have with each other. Examples include individual balance ability and the interaction between sway, pitch, roll, and heave. Another major challenge is the continuing study of the human body and its postural control mechanisms. A human is vastly more complicated than a stick figure when it comes to cognitive and physical balancing abilities.

A shortfall of this thesis was that it only considered one type of ship motion, sway. Since this thesis did not include pitch or roll in the analysis, the relationship between sway and other axes of ship motion remains to be determined. Therefore, further research should incorporate period and higher levels of acceleration than those used in the experiment, as well as the additional axes of pitch, roll, yaw, and heave. While lateral acceleration from sway clearly can induce MIIs, other research suggests that vertical acceleration from heave, as well as ship roll, may play an important part. Future research should investigate the different interactions with the various axes of ship motion because these complex motions are experienced on ships. Additionally, future research should incorporate ship design as a potential independent variable for MII prediction. For

example, different types of ships and hull designs can have a wide range of motion and frequency, which can influence the occurrence of MIIs on different ships. Better data on the relationship between ship design variables and MII occurrence could be used in design tradeoffs and risk mitigation.

Another limitation of this study was the motion base displacement limitations and the time constraints. The ranges of acceleration and time due to the limited displacement capability of the motion base led to a restricted range of acceleration and period. These limits reduced the range of MII occurrence that could be tested and would have yielded a more complete logistic model. Further research should attempt to find motion platforms that allow for accelerations up to 1 G force and periods in excess of two seconds. Also, Crossland and Lloyd (1993) suggested the importance of the friction coefficient between the shoe and the floor surface of a typical naval vessel. The experiment for this thesis did not fully control for coefficient of friction but did use 3M safety walk friction tape. Likewise, the type of shoe sole was not entirely controlled, as subjects were asked to wear tennis shoes or hiking boots or the like. More careful control of the friction coefficient is needed in future studies. Finally, when performing experiments on a motion base, it is important to perform a few practice trials to mitigate any practice effect that could influence the statistical models.

Future studies also should ensure that the subjects fit a range of age, weight, and height parameters consistent with the typical Navy population. Ship designers, as well as researchers continuing the improvement of MII models, should consider the period of acceleration because the duration of acceleration creates higher probabilities of MII occurrence. More data are needed to validate the findings that seem to conflict with ship motion envelopes from Figure 2 suggested by Baitis et al. (1984). The level of G force from the earlier study severely over-predicted the MIIs recorded in our data.

Finally, the author suggests adding MIIs into military planning and design documents. An example is the MLSTD 1472G, which outlines the design criteria for human engineering. MIIs should be included in the design and acquisition process early so that any MII problems can be prevented or mitigated early in the process to lead to cost savings because early changes are easier to implement than later ones. In the future,

researchers may want to consider the other domains of HSI, such as training. If sailors can experience conditions in a safe environment and learn how to perform tasks well in adverse motion conditions, the accuracy of MII prediction models could be improved and potentially limit future mishaps related to MIIs.

APPENDIX A. PRE-TEST QUESTIONNAIRE

1) Have you been ill in the past week? (☑ Check one answer only) ☐ Yes ☐ No

   a) If "YES", please indicate the nature of the illness (flu, cold, etc ______________________

   b) If "YES", please indicate the severity of the illness (☑ one answer only):
      ☐ Mild
      ☐ Moderate
      ☐ Severe

   c) If "YES", please indicate the length of illness: _____ (Hours or Days)

   d) If "YES", please indicate the major symptoms (list):the illness (flu, cold, etc ______________________

   e) If "YES", please indicate whether you are you fully recovered? (☑ one answer only) ☐ Yes ☐ No

2) Have you used any medication (either over-the-counter or prescription during the last 24 hours? (☑ one answer only) ☐ Yes ☐ No

   a) If "YES", please indicate all medications you have used in the past 24 hours. (if possible, specify type, dosage, and time taken):

   ____

3) Have you consumed any alcohol (beer, wine, hard liquor, etc) during the last 24 hours? (☑ one answer only) ☐ Yes ☐ No

4) Did you have breakfast this morning? (☑ one answer only) ☐ Yes ☐ No

5) How many caffeinated drinks have you consumed today? (coffee, tea, caffeinated beverages, etc) (☑ one answer only)
   ☐ None
   ☐ 1
   ☐ 2
   ☐ More

6) How many hours of <u>actual sleep</u> did you get last night? (This may be different than the number of hours you spent in bed) ___________[hours

7) Was that amount of sleep sufficient? (☑ one answer only) ☐ Yes ☐ No

8) Please list any other comments regarding your present physical state, which might affect your performance on our test:

____

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APPENDIX B. POST-TEST QUESTIONNAIRE

1. Please provide an overall rate of the severity of Motion Induced Interruptions during your data collection session.

[*Motion Induced Interruptions are all kinds of interruptions in your duty caused by ship's motion. If standing, an MII could be: sliding, losing your stance, not being able to walk, or having to get hold of anything firm so as to continue conducting your task. If seated, an MII could be: hold your chair so as not to slide, hold your console so as to continue watching the scope, unusual difficulty in using your keyboard or other controls due to ship's motion. In general, whenever the ship's motion is making you stop what you have been doing, even for a short amount of time, it is assumed to be an MII].*

Not at all — Mild — Severe

-3 -2 -1 0 1 2 3

2. Using the left scale below, rate the degree you experienced the statements at the right during your data collection session. Please put a number from 1 –9 in each of the 16 items.

<u>**Rate Scale**</u>	<u>**I felt:**</u>	
Not at all — **Severely** 1 2 3 4 5 6 7 8 9	1. Sick to my stomach	___________
	2. Faint-like	___________
	3. Annoyed/ irritated	___________
	4. Sweaty	___________
	5. Queasy	___________
	6. Lightheaded	___________
	7. Drowsy	___________
	8. Clammy/ cold sweat	___________
	9. Disoriented	___________
	10. Tired/ fatigued	___________
	11. Nauseated	___________
	12. Hot/ warm	___________
	13. Dizzy	___________
	14. Like I was spinning	___________
	15. As if I may vomit	___________
	16. Uneasy	___________

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APPENDIX C. RECRUITING SCRIPT

Motion Induced Interruptions (MII): An Opportunity to Participate in Research

This research project is being conducted by the Naval Postgraduate School and NSWC-PC to provide data to improve predictions of MIIs due to ship motion. MIIs are any imbalance, slip, trip, or hand-hold to maintain balance. If you choose to participate, you will be asked to stand on a motion platform and maintain your stance under a variety of motion conditions. A safety harness will ensure that you cannot fall, trip, or slip. You will wear a garment embedded with reflectors that will enable a Vicon Motion Capture system to record the motion of your head, knees, and ankles as you maintain your balance. We expect to collect data on approximately 30 people. Participation will require approximately 1.5 hours of your time. The potential risks are: you could "fall" approximately 2–3 inches before being supported by the safety harness. The garment embedded with reflectors could be uncomfortable if the sizes do not accommodate you. Your confidentiality and personally identifiable information will be protected by assigning an identification number. Your name will not be used or associated with the data.

You will not be qualified to participate if you have had medical issues such as vestibular, balance, vertigo, dizziness, postural disequilibrium, migraines, or injuries of back, leg or ankles.

The Navy's ability to improve predictive models of MII will be a general benefit of this research. Participation in this study is voluntary. You can withdraw at any time without consequence. Please contact Prof Michael McCauley at memccaul@nps.edu (or phone 831 656 2191 if you have any questions.
If you have questions related to risk, safety, PII, or other IRB issues, you may contact the NPS IRB Chair, CAPT John Schmidt, at jkschmid@nps.edu

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APPENDIX D. INFORMED CONSENT SHEET

Naval Postgraduate School
Consent to Participate in Research

Introduction. You are invited to participate in a research study entitled “Motion Induced Interruptions and Postural Equilibrium.” The purpose of the research is to improve our understanding of the limits of normal postural equilibrium so that we can maintain human performance and safety aboard ships.

Procedures. You will be exposed to motion (roll and sway) similar to standing on the deck of a ship. Your only task will be to maintain normal balance while standing on the motion platform. You will wear a garment with small reflectors attached to enable the Vicon infrared Motion Capture system to measure head motion and knee and ankle angles while you are on the motion platform. Another video camera will be used to record the sessions and it is possible that your face might be seen on that video record. If any video images are used for presentation or reports, faces will be de-identified. No names will be associated with the data. Approximately 30 volunteers will participate in this study. The total time of your participation is expected to be 90 minutes. All Participants will experience a series of different motion conditions consisting of combinations of roll and sway. You will be wearing a safety harness that will support you in the event that you slip or lose your balance. The safety harness will prevent you from falling more than a few inches. Please wear tennis shoes, walking shoes, or other shoes with good traction during this data collection period.

Disqualifying Conditions. You will not be qualified to participate if you have had medical issues such as vestibular dysfunction, loss of balance, vertigo, dizziness, postural disequilibrium, migraines, or injuries of back, leg or ankles.

Location. The lab research will take place in the Biodynamics Lab, which is on the south side of BLDG 431at NSWC Panama City Division.

Voluntary Nature of the Study. Your participation in this study is strictly voluntary. If you choose to participate, you can change your mind at any time and withdraw from the study. You will not be penalized in any way or lose any benefits to which you would otherwise be entitled if you choose not to participate in this study or to withdraw. The alternative to participating in the research is to not participate in the research.

Potential Risks and Discomforts. The potential risks of participating in this study are:

- Slip or loss of balance will result in the safety harness bearing your weight after a descent of approximately 3 inches
- Safety measures are focused on the availability, appropriateness, and proper deployment of the safety harness
- A nearby medical team is prepared to provide medical care or advice, if needed
- No resources have been set aside to pay for medical expenses
- Wearing the clothing with the reflectors imbedded could potentially be uncomfortable if it does not fit you well
- It is possible that susceptible individuals could develop symptoms of motion sickness
- No other physical, psychological, social, economic, or legal risks are foreseen.

Anticipated Benefits. Anticipated benefits from this study are improved models to predict the incidence of MIIs of sailors aboard navy ships. These improved models of ship motion will contribute to the design of hulls, deck surfaces, hand-holds, and procedures to operate in higher sea states.

Compensation for Participation. You will receive no compensation for your participation.

Confidentiality & Privacy Act. Any data or information that is obtained during this study will be kept confidential to the full extent permitted by law. An identification number will be assigned to your data for the purposes of this research. Your name will **not** be included in the database. Your name will occur only in the form of your signature on this Informed Consent form. The Informed Consent forms will be stored by the Principal Investigator (PI) in a locked cabinet in a locked office. However, it is possible that the researcher may be required to divulge information obtained in the course of this research to the subject's chain of command or other legal body.

Points of Contact. In case of a medical emergency, the test team will notify the following:

Command Duty Officer (CDO): 850-628-6532

Dispensary: 850-234-4177

If you have any questions or comments about the research, or you experience an injury or have questions about any discomforts that you experience while taking part in this study please contact the Principal Investigator, Dr. Michael McCauley, 831 656 2191, memccaul@nps.edu

Questions about your rights as a research subject or any other concerns may be addressed to the Naval Postgraduate School IRB Chair, CAPT John Schmidt, USN, 831-656-3864, jkschmid@nps.edu

Statement of Consent. I have read the information provided above. I have been given the opportunity to ask questions and all the questions have been answered to my satisfaction. I have been provided a copy of this form for my records and I agree to participate in this study. I understand that by agreeing to participate in this research and signing this form, I do not waive any of my legal rights.

______________________________	______________
Participant’s Signature	Date
______________________________	______________
Researcher’s Signature	Date

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APPENDIX E. LOGISTIC REGRESSION TABLE

MII Logistic Models									Whole Model Test		
Model	Predictors	$P(\beta_0)$	$P(\beta X_1)$	$P(\beta X_2)$	$P(\beta X_3)$	$P(\beta X_4)$	$P(\beta X_5)$	$P(\beta X_6)$	χ^2	$P(\chi^2)$	R^2
A	X_1	0.0001	0.0001						100.95	0.0001	0.117
B	X_2	0.0045		0.2811					1.17	0.2800	0.001
C	X_5	0.7429					0.2462		1.37	0.2419	0.002
D	X_6	0.0001						0.0199	5.51	0.0189	0.006
E	X_1, X_2	0.0001	0.0001	0.0001					154.64	0.0001	0.179
F	X_1, X_6	0.0001	0.0001					0.0117	107.47	0.0001	0.124
G	X_1, X_2, X_3	0.0001	0.0001	0.0001	0.0075				161.74	0.0001	0.187
H	X_1, X_2, X_3, X_5	0.0001	0.0001	0.0001	0.0073		0.1818		163.56	0.0001	0.189
I	X_1, X_2, X_3, X_6	0.0001	0.0001	0.0001	0.0071			0.0081	168.90	0.0001	0.195
J	X_1, X_2, X_3,X_5, X_6	0.0001	0.0001	0.0001	0.0068		0.0449	0.0023	173.06	0.0001	0.200
K	X_1, X_2, X_4	0.0001	0.0001	0.0001		0.0001			169.79	0.0001	0.196
L	X_1, X_2, X_4, X_5	0.0001	0.0001	0.0001		0.0001	0.1783		171.62	0.0001	0.198
M	X_1, X_2, X_4, X_6	0.0001	0.0001	0.0001		0.0001		0.0074	177.08	0.0001	0.204
N	X_1, X_2, X_4, X_5, X_6	0.0001	0.0001	0.0001		0.0001	0.0430	0.0021	181.32	0.0001	0.209

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